THE EVOLUTION AND DISINTEGRATION OF MATTER.

By Frank Wigglesworth Clarke.

INTRODUCTION.

In any attempt to study the evolution of matter it is necessary to begin with its simplest known forms, the so-called chemical elements. During a great part of the nineteenth century many philosophical chemists held a vague belief that these elements were not distinct entities but manifestations of one primal substance—the protyle, as it is sometimes called. Other chemists, more conservative, looked askance at all such speculations and held fast to what they regarded as established facts. To them an element was something distinct from other kinds of matter, a substance which could neither be decomposed nor transmuted into anything else. This belief, however, was based entirely upon negative evidence—the inadequacy of our existing resources to produce such sweeping changes. Many important facts were ignored, and especially the fact that the elements are connected by very intimate relations, such as are best shown in the periodic law of Mendeléef, who, from gaps in his table of atomic weights, predicted the existence of three unknown metals, which have since been discovered. For these metals, scandium, gallium, and germanium, he foretold not only their atomic weights but also their most characteristic physical properties and the sort of compounds that each one would form. His prophecies have been verified in every essential particular. One obvious conclusion was soon drawn from Mendeléef's "law," although he was too cautious to admit it, namely, that the chemical elements must have had some community of origin. The philosophical speculations as to their nature were fully justified.

In 1873 I ventured to publish the suggestion that the evolution of planets from nebulae was accompanied by an evolution of the chemical elements.[1] The validity of the nebular hypothesis was assumed, and the progressive chemical complexity of the heavenly bodies gave my argument its plausibility. The nebulae are chemically simple, the hotter stars more complex, the cooler stars and the Sun still more so, and the solid Earth the most complicated of all. The evidence for this statement was found in the spectroscopic researches of Huggins and Secchi, which seemed to me to be conclusive, although defective in one respect: instead of helium in the nebulae they reported nitrogen, for helium was yet to be discovered. This defect, however, did not invalidate my conclusions, which were promptly denounced as heretical but which have since been accepted as quite orthodox. Nearly a year later Lockyer[2] put forth an analogous suggestion, based upon evidence of the same sort but starting from the other end. That is, he assumed that in the hotter stars the elements were dissociated, and his suggestion was received with a good deal of favor. As to the origin of the dissociated elements he had nothing to say. That the elements are really decomposable was the substance of his suggestion, which he followed up in detail in his later publications.

With the discovery of radioactivity by Becquerel and of radium by Madame Curie a new era in chemistry began. It was at once found that at least some of the elements were really unstable; and the evolution of helium from radium, discovered by Ramsay and Soddy, made the evidence complete. A derivation of one element from another had actually been observed.

These discoveries opened a new field of research; and it was soon found that the elements at the top of the atomic-weight scale, namely, uranium and thorium, are spontaneously but slowly decaying, yielding more than thirty new substances which differ widely in

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[1] Clarke, F. W., Evolution and the spectroscope: Pop. Sci. Monthly, January, 1873.

[2] Lockyer, J. N., Roy. Soc. Proc., vol. 21, p. 513; paper dated Nov. 20, 1873.

stability. To each one a half-life period is assigned, some of them measured in thousands of years, others in fractions of a second. Among these substances are two new varieties of lead—one derived from uranium, the other from thorium—which chemically are not distinguishable from ordinary or normal lead except by differences in their atomic weight and their specific gravity. The lead from thorium has an atomic weight about a unit higher and that from uranium about a unit lower than the atomic weight of normal lead. To this class of facts I shall recur later, as evidence in support of my arguments. That chemical elements can decay is the essential fact to be remembered.

That the chemical elements were formed by a process of evolution from the simplest forms of matter can hardly be doubted now, but the process is not yet ended. They were developed at high temperatures; but when a certain stage was reached in the cooling mass they began to combine with one another to form the new class of substances which are known as compounds. These substances obviously represent an advanced degree of complexity, with corresponding instability; and with varying conditions both combination and decomposition, such as are reproducible by human agencies, constantly occur. By this extension of the evolutionary process the solid Earth was built up, but in principle the process is the same throughout. From the formation of the first elements to the chemical changes now taking place upon the Earth there is no real interruption. One line of progress has been followed until a maximum of natural complexity and instability is reached in the organic compounds that form the basis of all physical life, whether vegetable or animal. The same fundamental matter, governed by the same fundamental laws, appears from beginning to end of the evolutionary process.

THE EVOLUTION OF THE CHEMICAL ELEMENTS.

In any attempt to discuss the evolution of the chemical elements we have for guidance some facts and many analogies. That the most complex elements are unstable we have already seen, and it is suspected that all the others follow the same rule. Potassium and rubidium are feebly radioactive, a property which is an evidence of instability, and other confirmatory evidence will be cited later. Stability, however, is a relative term, and a substance that is stable under certain conditions becomes unstable under others. The prime factors that determine external stability are temperature, pressure, and chemical environment. For example, some compounds that are stable in anhydrous surroundings are decomposed in presence of water. Calcium carbonate, under ordinary conditions, is divided at high temperatures into carbon dioxide and lime, but heated in a steel bomb it not only remains undecomposed but may even be melted, to form upon cooling a crystalline marble. Examples like this might be multiplied indefinitely. As a rule stability diminishes with increasing temperature but is favored by increased pressure. We may also assume that the more symmetrical an atom or compound is the more stable it is likely to be.

Now, to return to our main problem, was the evolution of the elements a regular progression, such as might be represented by a smooth curve or a straight line; or was it irregular and quite independent of their order in the scale of atomic weights? To answer this question we must try to imagine what happened in the development of the larger masses, the nebulae and the stars. On this subject there is a plausible hypothesis which has been favored by many astronomers—namely, that the nebula at first was relatively cool, that the temperature gradually rose to that of the hottest stars and then regularly declined to that of the end product of the series, the solid planet. A gaseous mass, contracting under the influence of gravitation, became warmer; at its center, where the pressure was greatest, the increasing condensation generated still higher degrees of temperature, until a luminous nucleus was formed. As condensation went on with increasing intensities of pressure, the temperature continued to rise until the heat generated by compression was less than that lost by radiation into space, when cooling began. Although this hypothesis, in its crude form, is not universally accepted, it nevertheless gives a fair conception of that part of the evidence with which we are now concerned. The process of evolution from cool to hot and then to cool again is fairly outlined. The nucleus of the original nebula has its modern representative in the Sun.

In all the foregoing discussion it has been tacitly assumed that the nebula from which the solar system was developed was similar in all essential respects to the planetary nebulae. The latter, as shown by their spectra, consist mainly of hydrogen, helium, and nebulium, with slight traces in some of them of carbon, nitrogen, and perhaps other elements. Nebulium is known only from its lines in the spectrum, and its atomic weight has been estimated by Fabry and Buisson as 2.7, placing it between hydrogen and helium. In any further study of relations between the atomic weights of the elements, nebulium must be taken into account, and perhaps also coronium, so called from its lines in the spectrum of the solar corona. From its position in the corona it is assumed to be lighter than hydrogen and so would seem to be an even more primitive element. That possibility can not be considered here; we must limit ourselves to the conditions actually seen in the nebulae. No assumption is made as to the possible ancestry of the nebular elements; they are the visible beginnings.

Passing from the nebulae to the stars and finally to the planets, the course of evolution has been one of uninterrupted gradations. There are no sharp lines of demarcation between one class and another. As for the elements their evolution has been admirably summarized by Campbell[3] in his lectures on the evolution of the stars. Without literal quotation and accepting the Harvard classification of the stars, I may briefly outline Campbell's summary as follows: After the gaseous nebulae there are first the blue stars of classes A and B. In class B, known as the helium stars, the hydrogen and helium lines are conspicuous, and in their later stages silicon, oxygen, and nitrogen are represented by a few absorption lines. In class A the hydrogen lines are the most prominent, and helium has nearly disappeared. Lines of magnesium and calcium are also conspicuous, and those of iron and titanium are beginning to appear.

In the spectra of stars of class F, the bluish-yellow stars, the metallic lines increase rapidly in prominence; and in those of the yellow stars of class G they appear in great number. Hydrogen is much less conspicuous. In the spectra of the reddish-yellow stars of class K, which are weak in violet light, the metallic lines are more evident, and still more in those of the red stars of class M, in which the spectra also show absorption bands attributed to titanium oxide. In the spectra of the very red stars of class N the violet end of the spectrum is almost entirely lacking, the metallic absorption is very strong, and bands representing carbon oxides are conspicuous.

Such, in brief, was the probable course of elemental evolution in the passage from a gaseous nebula to the coolest and oldest stars. It is not necessary for my purpose to go more into detail on this phase of my subject. The literature relative to solar and stellar spectra is very extensive and is steadily increasing in volume. It involves many questions that I can not attempt to consider, even if I felt myself competent to do so. That the evolution of the elements has actually taken place seems to be established, and I must limit myself to some of the chemical problems that are suggested by it.

Now, it is easy to see that in the process of evolution from nebula to Sun an orderly development of the elements could hardly have been possible. With changing pressure, changing temperature, and changing environment all the conditions required for a regular progression according to the order of the atomic weights were lacking. In the hotter stars only the simplest and most stable elements were formed, and these in the greatest abundance. We have already seen that magnesium, calcium, titanium, and iron were among the earliest to appear, and that the others, between helium (atomic weight 4) and iron, either came later or were developed at first in much smaller quantities. As cooling went on more and more elements were generated, and in the Sun all the possible elements are presumably present, although only about half of them have been actually detected. It is conceivable that elements of different degrees of stability may have been formed simultaneously, one in that part of the cooling mass where the temperature and pressure were highest, another farther away from the center, under less rigorous conditions. This suggestion, however, is something which can not be proved. If the three

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[3] Campbell, W. W., Pop. Sci. Monthly, vol. 87, p. 209, 1915; Sci. Monthly, vol. 1, pp. 1, 177, 238, 1915.

nebular elements were the raw material from which the other elements were built, their relative amounts must have been continually changing, so that as each new element appeared a new environment was established for all that followed. At some time early in the course of evolution nebulium seems to have vanished, for its lines do not appear in the spectrum of any true star. Was it completely absorbed in building other elements? The question is easy to ask but very difficult to answer.

That the cooling of a star made the formation of the less stable elements possible has already been assumed. But was the rate of cooling uniform, or was it subject to fluctuations? To answer this question we must bear in mind the clear distinction between atoms and molecules, for here the elements as we know them differ widely. Some molecules, like those of zinc, cadmium, mercury, and the inert gases of the helium group, are monatomic. Hydrogen, nitrogen, oxygen, chlorine, bromine, and iodine are diatomic. Phosphorus and arsenic are tetratomic, and so on. For most of the elements we lack the positive information which we have for those just named. In ordinary chemical reactions the complex molecules are easily decomposed, and at high temperatures also decomposition is possible. The molecule of iodine, for example, is dissociated into its atoms at about 1,700° C., a temperature much lower than that of even the coolest stars. In the hotter stars all the elements present are probably in the atomic state, a considerable fall of temperature must take place before even diatomic molecules can be formed, and they may be regarded as a very primitive order of compounds. In the Sun and the cooler stars compounds in the ordinary sense of the term begin to appear and certain obvious consequences follow.

Whenever two or more free atoms unite to form a chemical compound heat is given out; and in most such unions, as in the formation of water from its elements, condensation has also its thermal value. I must here emphasize my use of the expression "free atoms," for they alone exist in the hotter stars. Such unions are rarely recognized in laboratory experiments, which deal not with direct combinations but nearly always with reactions. The heat of a reaction, which is usually called the heat of formation of a compound, is really the algebraic sum of three or more terms, some of which are positive and some negative. A reaction may be endothermic when the minus terms are in excess, as in the formation of hydriodic acid from its elements. Here the decomposition of the hydrogen and iodine molecules precedes the union of the momentarily free atoms.

In the evolution of the elements we have, then, first the formation of individual atoms, and as cooling goes on their union into diatomic and polyatomic molecules becomes possible. Heat is given out, and the rate of cooling must be somewhat retarded. Whether the retardation is great or small it is impossible to say; but some increase of temperature, even if it is very slight, may fairly be assumed. In short, the rate at which a star cools is in all probability subject to fluctuations, which may influence the development of the more complex and less stable elements. When compounds, as we understand them, begin to be formed, the heating effect is likely to be relatively larger. The cooling of our Sun is almost certainly subject to this sort of retardation, and so its existence as a heat-giving luminary may be considerably prolonged. Heat of chemical origin, with its attendant condensations, must be taken into account in any serious attempt to discover the sources of solar energy. The formation of molecular from atomic hydrogen would alone give out a vast amount of heat, about 82,000 calories per gram-molecule. The supposed formation of helium from hydrogen need not be considered. The helium of the Sun is probably primordial.

So far we have considered only the astronomical evidence relative to evolution, but that evidence is purely qualitative. For quantitative data we must study the so-called atomic weights and their relations, chemical and physical, with one another. The atomic weights, it must be remembered, are not absolute quantities, for no single atom has ever been directly weighed. They are really the expression of ratios, one element being assumed as a standard, with which the others can be compared, by methods that are so well known that it is not necessary to explain them here. These very elementary considerations are cited now because they are so familiar that they are often unconsciously ignored. If we think of the atomic weights as the combining numbers of the elements—that is, the proportions in which each one unites with others—it may be easier to avoid confusion of ideas.

At least three different standards of atomic weight have actually been in use. In the Berzelian system the atomic weight of oxygen was taken as 100, but that led to figures so large for most of the elements that they were difficult to remember and inconvenient to use. The system was therefore abandoned, and the atomic weight of the lightest element, hydrogen, was assumed as unity, a much more natural and satisfactory plan than that of Berzelius. The hydrogen unit, $H=1$, was in general acceptance until about 30 years ago, and it is still regarded favorably by many chemists. The only objection to it, at least until recently, was that very few of the atomic weights appeared as whole numbers, and the fractional parts were somewhat annoying. There was therefore a tendency among practical chemists to round the figures off to the nearest integers, for in many kinds of analytical work greater accuracy was not required.

On the hydrogen scale the atomic weight of oxygen is 15.876, or nearly 16, a figure which is the basis of the system of atomic weights now generally used. With $O=16$ a considerable number of other atomic weights become close approximations to whole numbers and therefore more convenient to handle. That is the principal reason why the oxygen standard has been so commonly accepted by chemists. This reason would be more valid if determinations of atomic weight had been made by direct comparison with oxygen, whereas as a matter of fact comparatively few such determinations have been at all satisfactory. With some exceptions, by far the larger number of the best modern determinations have been indirect, with silver, chlorine, and bromine as intermediaries. This indirection, however, does not imply inaccuracy. The actual measurements are those of ratios. To discuss this subject in detail would take me too far from my main theme.

We have already seen that hydrogen and helium are the two oldest elements of which we have any direct experimental knowledge. They also have the lowest atomic weight and are therefore the simplest. The astronomical and chemical lines of evidence are in complete harmony. Nebulium may be left temporarily out of account. Hydrogen and helium, then, are the two elements with which to begin any detailed study of elemental evolution. The atomic weight of hydrogen, 1.0078, is the starting point, with helium next in order. From these elements all other forms of matter may have been derived. There is much evidence in favor of this suggestion, although anything like absolute proof is lacking and perhaps unattainable.

Of the mechanism of the processes by which the elements were built up we have no positive knowledge. It is, however, in the highest degree probable that they were formed under extremely high temperatures and pressures, such as we can not hope to reproduce experimentally. That the evolution of the elements was accompanied by a progressive condensation is evident; and it is also clear that the contraction from the primal highly attenuated nebula to the solid planet was something enormous—so great that we can form no definite conception of its magnitude.

The two most promising lines of quantitative attack upon the problem of elementary evolution are as follows: One begins with a study of the numerical relations between the atomic weights of the elements, and the other with attempts to determine the structure of the atoms. I cite these in their historical order, which is not necessarily the one of greatest importance. The atomic theory was still in its infancy when in 1815 Prout suggested that all the atomic weights were whole numbers, based upon hydrogen as unity. Hydrogen, then, was the primordial element from which all others were derived. As most of the early determinations of atomic weight were rather crude and many of them close to integers, Prout's hypothesis was quite plausible. As the determinations became more exact it was found that few atomic weights were integral and that many of them differed widely from whole numbers. Prout's hypothesis was therefore set aside, although it has recently been revived upon a different foundation.

Since the time of Prout numberless attempts have been made to trace relationships between the atomic weights, but only a few of them were of any scientific value. The subject was a favorite one for a certain class of speculators, who generally started with preconceived opinions as to what atoms ought to be. Some interesting partial relations were pointed out by competent investigators, but the first advance of general significance was the reconstruction of the entire scheme of atomic weights by Cannizzaro, which brought it into harmony with the law of Avogadro. In this new system the old chemical equivalent of oxygen, O = 8, became O = 16, the present standard of value. Definite relations between the atomic weights now began to appear which previously were unsuspected, and these found expression in the "periodic law" of Mendeléef and the Lothar Meyer curve of atomic volumes. In both generalizations the starting point was the same, and the atomic weights were arranged in the order of increasing magnitude, from hydrogen up to uranium; or, as we can say now, the order of their atomic numbers, an expression which has become significant only within very recent years.

The periodic law, or periodic classification of the elements, is given in the following table. The atomic numbers precede the symbols of the elements, and the atomic weights are given below them. A different placing of the rare-earth metals will be considered later.

Periodic table of the elements.

[The upper numerals in the headings indicate natural groups; the lower numerals (arabic) indicate valencies. The rare-earth elements are inclosed within a thick line.]

0 0	I +1	II +2	III +3	IV +4	V −3–5	VI −2–6	VII −1–7	VIII ([a])
	1 H 1.008							
2 He 4.00	**3** Li 6.9	**4** Gl 9.1	**5** B 10.8	**6** C 12.00	**7** N 14.01	**8** O 16.00	**9** F 19.00	
10 Ne 20.2	**11** Na 23.00	**12** Mg 24.32	**13** Al 26.96	**14** Si 28.07	**15** P 31.04	**16** S 32.06	**17** Cl 35.46	
18 A 39.9	**19** K 39.1	**20** Ca 40.07	**21** Sc 45.1	**22** Ti 48.1	**23** V 51.0	**24** Cr 52.0	**25** Mn 54.93	**26** Fe 55.85 **27** Co 58.97 **28** Ni 58.68
	29 Cu 63.57	**30** Zn 65.37	**31** Ga 70.1	**32** Ge 72.5	**33** As 74.96	**34** Se 79.2	**35** Br 79.92	
36 Kr 82.92	**37** Rb 85.45	**38** Sr 87.83	**39** Y 89.33	**40** Zr 90.6	**41** Cb 93.5	**42** Mo 96.0	**43** —	**44** Ru 101.7 **45** Rh 102.9 **46** Pd 106.7
	47 Ag 107.88	**48** Cd 112.40	**49** In 114.8	**50** Sn 118.7	**51** Sb 121.7	**52** Te 127.5	**53** I 126.92	
54 Xe 130.2	**55** Cs 132.81	**56** Ba 137.37	**57** La 139.0	**58** Ce 140.25				
59 Pr 140.6	**60** Nd 144.3	**61** — **62** Sm 150.4	**63** Eu 152.0 **64** Gd 157.3	**65** Tb 159.2				
66 Ds 162.5	**67** Ho 163.5	**68** Er 167.7 **69** Tu 168.5	**70** Yb 173.5 **71** Lu 175	**72** —	**73** Ta 181.5	**74** W 184.0	**75** —	**76** Os 190.9 **77** Ir 193.1 **78** Pt 195.2
	79 Au 197.2	**80** Hg 200.6	**81** Tl 204.0	**82** Pb 207.2	**83** Bi 209.0	**84** [b]	**85** —	
86 Rn 222.0	**87** —	88 Ra 226.0	**89** [c]	**90** Th 232.15	**91** [d]	**92** U 238.2		

[a] Valencies diverse.

[b] Polonium?

[c] Actinium?

[d] Protoactinium?

The significance of the foregoing table, of which there are many variants, is evident at a glance. The elements in each vertical column are closely allied, forming the natural groups with which all chemists are familiar. The alkaline metals, the series calcium, strontium, and barium, the carbon group, and the halogens are examples of this regularity. In other words, similar elements appear at regular intervals and occupy similar places. If we follow any horizontal line of the table from left to right we find a progressive change of valency, and in both directions we find a systematic variation of properties. Broadly stated, the properties of the elements, chemical and physical, are periodic functions of their atomic weights; and this is the most general expression of the periodic law. At certain points in the table gaps are left, and these are believed to correspond to undiscovered elements. For three of the spaces that were vacant when Mendeléef announced the law he made specific predictions, which, as has already been stated, were verified by the discovery of scandium, gallium, and germanium. Radium and the inert gases, much more recently discovered, all fall into their proper places in the table and give additional emphasis to its validity. Place No. 72 is undoubtedly to be filled by the recently discovered element termed hafnium or celtium, two names which are at present in controversy. The names assigned to Nos. 84, 89, and 91 are provisional only and may not be sustained. The elements corresponding to Nos. 43, 61, 75, 85, and 87 are as yet unknown, although their properties can be predicted with a close approach to certainty.

The periodic table is also very suggestive as regards the chemical relations and modes of occurrence of the elements in nature. In the first place, the members of the same elementary group have similar properties, form similar compounds, and give similar reactions, and because of these conditions they are commonly found in more or less close association. Thus the platinum metals are seldom found apart from one another; chlorine, bromine, and iodine occur under very similar conditions; selenium is found in native sulphur; cadmium is extracted from ores of zinc; and so on through a long list of regularities. The group relations govern many of the associations that are actually observed, although they are modified by the conditions that influence chemical union. Even here, however, regularities are still apparent. In combination unlike elements seek one another, and yet there appears to be a preference for neighbors of approximately equivalent mass. For example, silicon follows aluminum in the scale of atomic weights, and in the crust of the earth silicates of aluminum are far the most abundant minerals. An even more striking example is furnished by the series oxygen, sulphur, selenium, and tellurium. Oxidized compounds of many elements are found in the mineral kingdom, but most of them are compounds of metals of low atomic weight. Above manganese, sulphides are abundant; but selenium and tellurium are more often united with the heavier metals silver, mercury, lead, or bismuth, and tellurium with gold. The elements of high atomic weight seem to seek one another, a tendency which is indicated in many directions, even though it may not be stated in the form of a precise law. The general rule is evident, but its full significance is not so clear.

One phase of the periodic law, equally suggestive with the preceding table, is shown in Lothar Meyer's curve of atomic volumes. When these volumes are plotted against the atomic weights they give a curve that consists of a series of undulations or waves of considerable amplitude. On these waves similar elements occupy similar positions—the alkaline metals at the crests, the heavier metals in the depressions, and the other elements in orderly arrangement between these extremes. The regularities are very striking and continue as far as the elements of the rare-earth group above cerium, where the waves flatten out, until at tantalum the curve becomes normal again. Similar curves can be drawn for other physical properties of the elements, with similar results. Richards,[4] for example, has superimposed upon the curve of atomic volumes curves representing compressibilities, coefficients of cubical expansion, and the reciprocals of the melting points. All four curves are similar in type and show the same periodicity. They are somewhat ragged, but nevertheless they tell the same story. The irregularities are due partly to defective data and partly to the fact that the physical constants were not

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[4] Richards, T. W., Am. Chem. Soc. Jour., vol. 37, p. 1649, 1915.

determined under strictly equivalent conditions. The atomic volumes, which are the ratios between the atomic weights and the specific gravities of the solid elements, are especially in need of revision. The specific gravities of some elements were determined at temperatures relatively near their melting points, those of others at temperatures 1,000 or more degrees below them. It is possible that if all could be determined at points near the absolute zero, or, as an alternative, at points just below the temperature of fusion, a smoother curve might be given.

The curve of atomic volumes, as given in Plate XXII, is reproduced, with the author's permission, from Professor A. W. Stewart's volume "Some physico-chemical themes" (London, 1922). In one respect it is likely to be misleading. The atomic volumes are calculated from the atomic weights, not from the atomic numbers.

In the region of the rare-earth metals, between cerium and tantalum, the regular evolution of the elements seems to have been interrupted, so that a systematic periodicity is no longer evident. These metals all resemble one another very closely and form compounds of similar type. Their normal oxides are all of the form R_2O_3, their chlorides are RCl_3, and so on, and they are therefore to be considered trivalent. Cerium, however, which is a member of this group, also forms a dioxide, and it is therefore possibly quadrivalent, although most of its compounds are of the trivalent type. The earlier elements of the group, which appear in the periodic scheme—namely, scandium, yttrium, and lanthanum—are all normal.

Furthermore, the rare earths occur in nature under similar conditions, they are almost everywhere intimately associated, they are difficult to separate, and their oxides are not easily reducible to metals. These very intimate relations need to be explained, and the curious flattening of the Lothar Meyer curve in the part of the atomic-weight scale which the rare-earth metals occupy gives us a clue to their mode of origin. It is evident that they must have been formed under very similar conditions, which changed but slightly as the atomic weights increased. In other words, the conditions were nearly constant, but not quite, for with absolute constancy there would have been only one element generated instead of at least a dozen.

The two preceding paragraphs lead at once to a very simple hypothesis. In the course of evolution from the hottest to the coolest stars there was probably a period of undeterminable duration when the rate of cooling and condensation was in some unknown way retarded, so that the conditions became nearly uniform. During this period, which was followed by one of increased activity, the elements of the rare-earth group were formed. This hypothesis gives a rational explanation of the known facts concerning these elements and is therefore, despite its speculative feature, legitimate. If it is sound, then the elements of the rare-earth series should appear in the periodic table as prolonging the trivalent group, and not be scattered under other groups to which they can not possibly belong.[5]

One more curiously suggestive relation connecting three distinct groups of elements deserves consideration here. The halogens, F, Cl, Br, I, are strongly electronegative; the alkaline metals, Li, Na, K, Rb, Cs, are strongly electropositive; and these two groups are separated by the inert gases, He, Ne, A, Kr, Xe. So we have the following triads: F, Ne, Na; Cl, A, K; Br, Kr, Rb; I, Xe, Cs. The atomic weights in each triad are consecutive. Another probable triad is incomplete; only He and Li are known. One more electronegative element is needed here, which should be a gas of greater chemical activity than fluorine and of lower atomic weight. Is nebulium, with atomic weight near 2.7, the missing member? If so its chemical activity might account for the nonappearance of its lines in the stellar spectra. Was it used in building other elements? That question I have asked already, but it is not yet answered. Here we enter the realm of pure speculation, the foundations of which are insecure. Speculation is of value only in so far as it is suggestive. The intervention of the inert gases between two groups of great chemical activity is well established, but I must leave its explanation to physicists and mathematicians.

Although the periodic classification of the elements is now thoroughly established, there

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[5] In this mode of placing the rare-earth metals, I find that I have been anticipated by Dr. C. Renz (Zeitschr. anorg. allgem. Chemie, vol. 122, p. 143, 1922). My interpretation of the scheme is, I think, new.

are certain details of it that remain to be adequately investigated. The numerical relations between the atomic weights can not at present be discussed with any approach to finality. The problem is complicated by frequent changes—for example, within the last two or three years the atomic weight of scandium has been raised from 44 to 45, that of bismuth from 208 to 209, and that of antimony from 120.2 to 121.77. Recent investigations relative to "isotopes" have thrown doubt upon the definiteness of the atomic weights as they have been actually determined; and until that question is settled experimentally the true numerical relations must remain uncertain. The theoretical atomic weights will be considered later.[6]

Now, using the word in its chemical sense, let us ask: What is an atom? Here many loose reasoners have gone astray and have assumed that because atoms have been found to be decomposable, the atomic theory is overthrown. They seem to regard the etymological meaning of the word as having ultimate significance, but etymology is an unsafe guide in the discussion of scientific problems. The technical significance of a word may be quite unrelated to its etymological history. What, for instance, does the word "chloroform" mean? According to etymology, a green ant!

In brief, the chemical atoms are now known to be complex, ranging from the comparatively simple hydrogen up to the highly complicated and unstable uranium. Each atom is supposed to consist of an electropositive nucleus, attended by one or many electrons of opposite sign. In the hydrogen atom there is one "planetary" electron, in helium two, and so on regularly up to 92 in uranium, at the present summit of the atomic-weight scale. These electrons are also supposed to be, above a certain small number near the beginning of the scale, arranged in rings or perhaps concentric shells around the nuclei. Whether they are revolving about the nuclei, like planets around the Sun, or are relatively at rest is an open question. Models that show the structure of atoms have been constructed, but they are not in complete agreement. The prevalent opinion regards each atom as resembling a miniature solar system, and the term "planetary electrons" is used to distinguish those around the nucleus from some which have found place within it. The mass of an atom is almost entirely concentrated in the nucleus, for it is known that the weight of a single electron is only about $\frac{1}{1800}$ of that of an atom of hydrogen, or 0.00054 on the ordinary scale of atomic weights.

On this foundation Rutherford [7] has erected his scheme of elementary evolution, starting with the hydrogen atom. The nucleus, or "proton," and the single electron are taken as the two fundamental constituents of all matter, whether element or compound, and these units are purely electrical. Prout's hypothesis has come to life again, but in a highly modified form.

The next important step in the study of atomic structure was taken by Moseley,[8] who from measurements of the X-ray spectra of the elements discovered relations which proved that "there is in the atom a fundamental quantity which increases by regular steps as we pass from one element to the next"—that is, the next in the ascending scale of atomic weight—and that "this quantity can only be the charge on the central positive nucleus." That charge increases with increasing atomic weight and so follows the order of the elements upward, or in other words the order of the atomic numbers H 1, He 2, Li 3 . . . Ca 20, Zn 30, and so on up to U 92. These numbers are now regarded by many physicists as of more fundamental importance than the atomic weights from which they were first derived. In the series of atomic numbers, just as in the periodic law, there are gaps that represent undiscovered elements. There is no place in the scheme, however, for nebulium or coronium. The atomic numbers may have to be revised.

Now, without rejecting Moseley's "law," we must admit that the experimental evidence for it is incomplete. The region of the metals of the rare earths needs to be investigated, so as to determine whether their atoms carry electrical charges in the order demanded by the law. Does their anomalous character show itself here? The curious relations of the inert

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[6] For a very complete history of the periodic law, see Venable, F. P., The periodic law, Easton, Pa., 1896—a valuable contribution to the history of chemistry.

[7] Rutherford, Sir Ernest, Nature, vol. 110, p. 182, 1922.

[8] Moseley, H. G. J., Philos. Mag., 6th ser., vol. 26, p. 1024, 1913; vol. 27, p. 703, 1914.

gases, which have already been pointed out, also need explanation. The periodic variations in the physical properties of the elements also seem to require adjustment to the law. The difficulties thus suggested may be more apparent than real, but they should not be ignored.

The question has often been asked whether the atomic weights of the elements are definite constants, or merely statistical averages of slightly differing values? The actual determinations were made on masses of material containing millions of atoms, which may or may not be exactly alike but are tacitly assumed to be so. To state the problem in different form, what are the elements as we really know them?

In a remarkable series of experiments Aston[9] has obtained evidence, which he regards as proof, of the complexity of the atomic weights as determined by chemical methods. Powerful positive rays in a magnetic field were driven upon a number of elements, which then gave on photographic plates what he calls their "mass spectra." These spectra show lines corresponding to whole-number atomic weights, which, with some exceptions, represent not the accepted values but some higher and some lower. The new lines, as interpreted by Aston, are due to "isotopes," and the elements yielding them are regarded as mixtures. The subject of isotopes I shall take up in the final section of this paper, where it properly belongs. A few elements gave mass spectra of single lines, which nearly agreed with the accepted atomic weights, and these Aston defines as "simple elements."

From the evidence furnished by the mass spectra Aston concludes that all the true atomic weights, including the isotopes but excepting hydrogen, are whole numbers. This rule he regards as fundamental, although it is based on O = 16 as the standard of values. But this standard was originally adopted as a matter of convenience and had at first no theoretical foundation. It seems, therefore, as if its importance is overrated. Nevertheless we may assume the validity of the rule and see how nearly the atomic weights of some of the "simple elements" conform to it. That is, How far do the real atomic weights diverge from the theoretical whole numbers? The figures are given in the following table:

	Atomic weight.		Divergence, 1 part in—
	Found.	Theoretical.	
Glucinum	9.018	9.0	500
Nitrogen	14.008	14.0	1,750
Aluminum	26.963	27.0	730
Phosphorus	31.04	31.0	773
Sulphur	32.06	32.0	540
Arsenic	74.96	75.0	1,875
Iodine	126.92	127.0	1,588
Caesium	132.81	133.0	700

These divergences are too large to be ascribable to experimental errors. The poorest of the atomic-weight determinations cited above is probably correct within 1 part in 3,000, and that of nitrogen is trustworthy, I think, within 1 part in 10,000. I base my opinion on a careful study of the methods by which each value was determined and especially on their concordance.

That the real and the ideal rarely coincide is well shown in the preceding table, and I venture to cite two well-known examples of such disagreement. Avogadro's law, that equal volumes of gases under equal conditions contain equal numbers of molecules is rigorously applicable only to ideally perfect gases. To the real gases with which we have to deal the law applies approximately and is subject to correction by the two small constants discovered by Van der Waals. The law of electrolytic dissociation is true only for infinitely dilute solutions, and solutions of that kind do not come within our experience. Under working conditions it may be nearly true. Now, if the whole-number rule for the atomic weights is theoretically sound, a supposition which is not yet proved, we may have to assume a distinction between perfect and imperfect elements, and for that assumption there is some justification. Uranium, as we know it, has been slowly decomposing for millions of years, and the uranium that remains is partly decayed. The atomic weight of the normal element as it was before decay began is quite unknown. Thorium offers a similar example, and it is furthermore very doubtful whether any thorium exists that is quite free from ionium of certainly lower atomic weight. In short, the

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[9] Aston, F. W., Isotopes, London, 1922. In this volume Aston gives a complete summary of his own researches, together with much material relative to Rutherford's work, Moseley's law, the periodic system, and related subjects.

radioactive elements are probably all imperfect in the same way. Are any other elements defective? That we can not say, unless we attempt to define a perfect element. Such an element should be absolutely stable and therefore undecomposable, and only the primal protyle would satisfy these conditions. Hydrogen is the simplest known form of matter, but is there nothing simpler? We do not know.

In Rutherford's scheme of elementary evolution he uses the hydrogen nucleus with its single electron as a primary unit, and helium, with four protons and two electrons, as a secondary unit. From hydrogen and helium nuclei and electrons the complex nuclei of all the other atoms are supposed to be built up. A system similar to this has been developed by Harkins,[10] who assumes another hypothetical unit of mass 3, composed of three protons and two electrons. This new unit may be equivalent to nebulium, but that is by no means certain. The system, however, works well and brings out some interesting relations between the atomic weights, which may be partly real and partly coincidental. Rutherford seems to neglect nebulium, and neither he nor Harkins takes into account coronium, of unknown atomic weight. Its possible importance, however, ought not to be ignored. Coronium surely exists and must play some part in the evolution of matter. In Nicholson's scheme of elemental evolution[11] coronium, nebulium, and a hypothetical protofluorine are utilized and given atomic weights. That of coronium is assumed to be a little more than half that of hydrogen.

So far the views of Rutherford and Harkins are in essential harmony with the astronomical evidence. Hydrogen and helium are two primary units from which other elements were developed, but in the electrical theory an assumption is made to which an alternative hypothesis is possible. The helium nucleus is supposed to be built up from four hydrogen nuclei or protons. But He = 4, and H = 1.0078; so that 4H is really 4.0312, or slightly less if the loss of two electrons is deducted. A loss of mass in forming helium is therefore assumed and is explained by an electromagnetic theory of "packing." For this explanation, which is not very clear, I must refer to the publications of Rutherford and Aston already cited.

Suppose now that helium instead of being a quasi polymer of hydrogen is really an independent entity of mass 4. This supposition may not be in complete agreement with the electrical theory of matter as that is now formulated, but it is sustained by some evidence. Hydrogen is chemically active, helium is inert, and it is not easy to see how four atoms of the one could coalesce to form an atom of the other. In the nebulae the two elements appear to be widely separated, with no suggestion of any other relation between them than that of a possible common ancestor. Furthermore, the alpha ray of radioactive transformations is an atom of helium, which shows no sign of further decomposition. A priori the new hypothesis is just as plausible as the other, although neither is completely proved. That the alleged loss of mass is not a necessary assumption seems to be clear. In the formation of compounds there is no indication of any "packing effect," although there may be very great condensation.

It is in the highest degree probable that hydrogen and helium are two fundamental elements in the evolution of matter. But nebulium should be considered with them as having some part, if only a subordinate one, in the evolutionary system. From the position of its lines in the spectrum of the great nebula of Orion, Fabry and Buisson, by interferometer measurements, found its atomic weight to be 2.7, or almost exactly $2\frac{2}{3}$. Now, the atomic weights of several other elements, taken as whole numbers, are even multiples of this figure and also of the atomic weight of helium.

From a much larger list I select the following atomic weights for comparison with that of nebulium and with one another; Helium, 4; oxygen, 16; magnesium, 24; sulphur, 32; calcium, 40; titanium, 48; iron, 56. Five of these elements, it will be remembered, are those which appear earliest in the hotter stars. Now, with nebulium (Nm) = $2\frac{2}{3}$, the comparison is as follows:

$3\,\mathrm{Nm} = 8 = 2\,\mathrm{He}$
$6\,\mathrm{Nm} = 16 = 4\,\mathrm{He} = \mathrm{O}$
$9\,\mathrm{Nm} = 24 = 6\,\mathrm{He}$
$12\,\mathrm{Nm} = 32 = 8\,\mathrm{He} = 2\,\mathrm{O}$
$15\,\mathrm{Nm} = 40 = 10\,\mathrm{He}$
$18\,\mathrm{Nm} = 48 = 12\,\mathrm{He} = 3\,\mathrm{O}$
$21\,\mathrm{Nm} = 56 = 14\,\mathrm{He}$

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[10] Harkins, W. D., Phys. Rev., 2d ser., vol. 15, pp. 73, 141, 1920.

[11] Nicholson, J. W., Philos. Mag., 6th ser., vol. 22, p. 864, 1911. Coronium and nebulium are also taken into account by Rydberg (Jour. chim. phys., vol. 12, p. 585, 1914).

Regarded superficially the foregoing figures are very suggestive, but they must not be taken too seriously. They may, perhaps, express approximate relations, and they show that nebulium deserves consideration in any scheme of atom building. It is, however, an unruly element, for it disturbs the order of atomic numbers, and its atomic weight is not integral. The latter irregularity is not serious, for five of the elements in the table have atomic weights that diverge appreciably from whole numbers. Whether the divergences indicate mixtures of isotopes remains to be seen. The table as it stands is an excellent example of the ease with which the theorist can find relations between the atomic weights if he is only allowed to take a few little liberties with the facts.

Two other sets of figures approximating atomic weights are worth citing here. Whole numbers are assumed, and the symbols represent the atomic weights:

$$\mathrm{Fe}=2\mathrm{Si}=4\mathrm{N}=8\mathrm{Li}=14\mathrm{He}$$
$$\mathrm{Mo}=2\mathrm{Ti}=3\mathrm{S}=4\mathrm{Mg}=6\mathrm{O}=8\mathrm{C}=24\mathrm{He}$$

These relations are very striking, but have they any real significance relative to the evolution of the elements? If we were to arrange 92 integers, taken at random between the atomic weights of hydrogen and uranium, and as nearly as possible equally spaced, should we not be likely to find many numerical relations between them? In short, is not the problem of the atomic weights something more than a mere numerical exercise? This question, I think, needs no answer. If many of the chemical atomic weights are merely "statistical averages" of two or more isotopic values, any attempt to discover exact mathematical relations between them will surely be futile.

Since the discovery of radioactivity atomic genealogists, if I may call them so, have been extremely busy. Their contributions to the literature of the subject are very numerous, and I can not undertake to summarize them here. Some of their publications are worthless, and some are extremely valuable, but nearly all are more or less one-sided, for they lay undue stress upon mathematical or physical or chemical data, and each writer ventures little out of his own special field. Not until all lines of evidence have been brought into convergence can the problem of elementary evolution be solved. The workers in different fields and with different outlooks must learn how to cooperate.

In every attempt that has heretofore been made to explain the evolution of the elements in detail there are difficulties which must be faced. Some of these difficulties have already been considered. The integrity of the atomic weights has been called in question, and the deviation of many of them from whole numbers has not been satisfactorily explained. The theory of atomic numbers is also incomplete, for it makes no allowance for possible elements simpler than hydrogen, or between hydrogen and helium; and it reverses the observed order of three pairs of elements, namely, potassium-argon, nickel-cobalt, and iodine-tellurium. That these reversals are justifiable is by no means certain. The positive evidence should not lightly be set aside.

In the last analysis the problem of elementary evolution seems to be one of equilibria, or, which is much the same thing, of relative stabilities; and the fundamental data are those which relate to atomic structure. On this subject there is as yet no general agreement, but the scheme that has been most favorably received is that developed by Rutherford and his colleagues, to which I have already referred.

At first sight Rutherford's scheme of evolution appears to be very simple and symmetrical, but it is by no means free from difficulties, and some of these lie at its very foundations. The light electron and the massive proton are defined as "atoms of negative and positive electricity"; but what these definitions mean is not clear. As the elements above helium are developed the nuclei or groups of protons become more and more complex, and just how the protons are held together is unexplained. The uranium atom is supposed to carry 92 electrons, and this complexity of structure accounts for the recognized instability of that element, as shown by the constant emission of helium from its nucleus, the very swift alpha rays. Between hydrogen and uranium the elements are arranged in the order of their atomic numbers, which represent not only the number of electrons in each atom but also the net electric charge carried by its nucleus. But what is meant by an electric charge upon an "atom" or cluster of "atoms" of electricity? Is there not something in the proton that is not electrical, which serves as the carrier? These questions I can not attempt to answer. They involve the fundamental hypothesis that matter and electricity are identical, which is certainly not proved.

One more doubtful feature of Rutherford's system remains to be noticed. It is assumed that the progression from the simplest to the most complex element is regular and uninterrupted, step by step. But the irregularity shown by the rare-earth elements in the periodic system seems to have been ignored, and this must be taken into account in any valid scheme of elementary evolution.

In what I have said so far I have not intended to be hypercritical. It seemed necessary to point out some of the difficulties that exist in all the schemes of elementary evolution, for to ignore them is to put obstacles in the way of progress. There is really more to be said in favor of the current theories of atomic structure than can be urged against them. All of them are attempts to interpret evidence, and each one is partly successful. Their agreements are more significant than their differences.

A scientific theory has two sides, one speculative, the other utilitarian. As a mere intellectual exercise it has little importance; its real value is in its ability to classify phenomena, to express their relations, and to point the way to new discoveries. In plain language, Does it work? If the prevailing theory of atomic structure is fundamentally sound it must satisfy these conditions. Hitherto it has been developed almost entirely in its physical and mathematical aspects; its chemical aspects have received too little consideration. It is on the chemical side that the theory is likely to be most severely tested. The complete study of any chemical reaction involves problems that are difficult to solve.

A chemical reaction may be described in a general way as a readjustment of equilibria. Let us consider one of the simplest, the formation of water from its elements as represented by the equation

$$2H_2 + O_2 = 2H_2O$$

Here three stable molecules are broken up, and two new stable molecules are formed; heat is generated, and three gaseous volumes are condensed to two. A further condensation to liquid water follows.

Now, in terms of atomic structure, what does this reaction mean? How was it that three elementary molecules could be disrupted and two new ones formed? Each hydrogen atom is supposed to consist of a nucleus with one electron, and each oxygen atom of a nucleus with eight electrons. What are these electrons doing, and what is the nucleus of the new molecule of water? Why does condensation take place, and why is heat emitted? Is the loss of heat due to an arrest of motion of two or more electrons? Moreover, by electrolysis the whole reaction can be reversed and the original equilibria reestablished. These questions are as yet unanswered, and they raise the larger question as to the nature of chemical affinity. If the theory of atomic structure is sound it should ultimately shed some light upon these problems.

Let us go a step further and consider a more complicated case, one of double decomposition. When solutions of barium chloride and sodium sulphate are mixed the following reaction occurs:

$$BaCl_2 + Na_2SO_4 = BaSO_4 + 2NaCl$$

Here we have five kinds of atoms and four different molecules, but three of the molecules are partly dissociated in solution. The barium sulphate, however, is thrown down in solid form, and the reaction is not reversible. All the problems suggested by the simpler reaction appear in this new equation, with others that are equally difficult to answer. What part does water play in this double decomposition? Why is the barium sulphate condensed to a solid from diffused ions in the initial solution? What are all the electrons doing, and what are the nuclei of the four compounds? I suspect that we are a long way from any complete answer to these questions. A theory of atomic structure, to be satisfactory to chemists, must give them some clear conceptions regarding the mechanism of chemical reactions.

Examples like these might be multiplied indefinitely, but all give rise to similar problems. In every case, if we accept the electric theory of matter, we must ask the same questions: What are the electrons doing, and how are the protons held together? If for the moment we confine our attention to the evolution of the atoms, we have also to consider the conditions, external and internal, that determine their relative stability. The external conditions have already been defined; the internal conditions are those of atomic structure, its simplicity or complexity, the symmetry of the atom, and the exact electrical balance between electrons and nuclei. A simple, symmetrical atom is likely to be very stable; a complicated structure implies instability. The terms stable and unstable are of course relative; they have no absolute meaning.

In the study of elementary evolution two basic problems underlie all the others. What is the process, and what are its products? Unfortunately we are unable to reproduce the process artificially. We can not hope to build up elements as they are built up in the stars, for the conditions are too severe for us to meet. We can, however, tear down some of the more complex structures and so get some light upon their genesis. That work is now just beginning, and from it we may reasonably expect to arrive at more definite conclusions. The products of devolution we can study directly, and the two lines of evidence ought ultimately to converge.

I venture now to point out one analogy that may have some significance with regard to the character of the elements. Organic chemistry is defined as the chemistry of carbon compounds, and atoms of carbon, in chains or rings, form the skeleton, or framework, or scaffolding of the whole edifice. May not the elements be built in a similar way with atoms of helium instead of carbon? This suggestion is not altogether new: it is implied in the hydrogen-helium scheme of evolution; but here it would include nebulium as a possible part of the superstructure. It is at least worth testing, although I am not blind to possible difficulties in its detailed application.

In all discussions relative to cosmogony there is a danger of going too fast and too far. That statement holds true in the present discussion. We know that the same elements appear throughout the stellar universe, and we must assume that their evolution was governed by the same fundamental laws of chemistry and physics. But we can not assume that all solar systems are exactly like ours in chemical composition. The parent nebulae may have differed in the relative proportions of their component gases, and the rate of cooling in passing from nebula to star was not necessarily everywhere the same. It is conceivable, therefore, that different solar systems may have generated the elements in somewhat different order, and not invariably in the same relative abundance, but these dissimilarities, if they exist, are probably not very large. To assume that anything like absolute uniformity exists would, however, be quite unwarranted.

Before we pass on to the subject of the evolution of compounds, it seems well to consider briefly a question relative to what may be called scientific utility. A scientific theory, to be useful, must meet the conditions that have been stated in a former paragraph and so prove its value. Such a theory is the atomic theory of Dalton, which is the corner stone of modern chemistry. Even the modern electrical conception of matter is based upon it. Many examples of similar purport might be cited.

It has recently been asserted by high authorities that "a chemical element is defined by its atomic number." How far is this conception sustained by the test of its utility? How far can it be used in dealing with chemical problems? May it not be better to say that a chemical element is defined by the aggregate of all its properties? The theory of atomic numbers covers only part of the ground.

The atomic numbers, it should be remembered, assign to each element its place in the order of ascending atomic magnitude. That is, the atomic weights came first, and the atomic numbers followed. It is now held, however, that the atomic numbers also represent the electric charges carried by the nuclei of the atoms, and the number of electrons belonging to each one. These claims may be valid, but they have not yet been as thoroughly tested as they should be. Will they guide future research and be fruitful in discoveries? That remains to be seen.

In practical utility the atomic weights are far more important than the atomic numbers. They are the fundamental quantities of chemical arithmetic and are in constant use in chemical calculations. To the working chemist they are indispensable. In the calculation of analyses, or of the proportions in which substances shall be taken in order to perform a given quantitative reaction, atomic weights are always, directly or indirectly, employed.

They are expressed in every chemical formula and in every chemical equation, and the atomic numbers can never replace them. The laws of chemical combination are based upon the combining numbers of the elements, and these are the atomic weights. In the periodic table the atomic weights and the atomic numbers both appear; but the periodicity of physical properties is best shown in curves like that of atomic volumes. Such curves show that the physical properties of the elements are periodic functions of the atomic weights. The alleged supremacy of the atomic numbers is by no means established. The usefulness of the atomic weights is independent of the order in which they are arranged.

After all, the physical quantities that are directly related to the atomic numbers are functions of the atomic masses, and so, too, are the atomic numbers.

That the theories of atomic structure which have so far been proposed are not in close agreement has already been pointed out. One partial theory, however, deserves mention here—that of the tetrahedral carbon atom as advanced independently by Van't Hoff and by Le Bel. That theory was framed in order to account for the different optical properties of the two tartaric acids, but it did much more than that. It was the foundation of stereochemistry, a new field of research, which has been wonderfully fruitful in important discoveries. The theory was devised before electrons were known, but it is evidently adjustable to the electronic conception of matter. No such adjustment is needed, however to emphasize its proved efficiency.

NOTE.—For a critical summary of the principal theories of atomic structure see Stewart, A. W., Some physico-chemical themes, pp. 373–397, 1922. See also Webster, D. L., and Page, L., Nat. Research Council Bull. 14, 1921.

THE EVOLUTION OF COMPOUNDS.

It has already been said that the process of evolution is continuous, from the simplest forms of matter to the most complex. Between elements and compounds there is no sharp line of demarcation, and one class shades into the other. In one sense the elements are really composite, primary compounds built up from a few fundamental substances, and they are characterized by great relative stability. They have so far not been formed by any artificial synthesis, and they are not decomposable by any of the ordinary processes of the chemical laboratory. The reported decomposition by means of powerful radiations or by electrical currents of the greatest intensity will be considered in another section of this memoir. Compounds, on the other hand, are formed by the combination of elements, into which they are easily separated and from which many of them can be prepared synthetically. The terms element and compound are used here in their ordinary technical significance and are not subject to any verbal quibbling. The elements form one definite class of substances, the compounds form another, and the chief difference between them is one of stability.

Between the formation of an element and the formation of a compound there is, however, another difference. The first stage of the process was one that required a vast period of time; the second stage is marked by rapidity. The series of elements was slowly formed, and their rate of decay, as shown between uranium and lead, is also relatively slow. The formation and decomposition of compounds, on the other hand, is rapid; and for some compounds the rate is measurable. The distinction is not absolutely definite, for some of the short-lived products of radioactive decay seem to be exceptions to the rule, which in general may be stated as follows: The process of evolution is characterized by progressive acceleration, being slow at first and becoming gradually more and more rapid. Its rate of acceleration may not be uniform, but its general drift is clear. It follows the line from the simplest substances to the most complex. In all vital processes the ease and rapidity with which compounds are formed and developed is evident, and some of these substances are extremely complicated.

Just as an infinite number of words can be formed from the 26 letters of the alphabet, so myriads of compounds can be built up from comparatively few elements. At least a hundred thousand compounds are already known, but by far the greater number of them are artificial products and have no place among the relatively simple substances that are developed in a cooling globe. In that laboratory the possibilities of combination are limited. We have already seen that bands of a few compounds, such as the oxides of carbon and possibly cyanogen, have been detected in the spectra of the cooler stars and the Sun, but these compounds are all gaseous. Heavy, solid compounds would probably sink below the reversing layer and not be recognized in the spectrum. Can we decide, with any approach to probability, what solid compounds would be likely to be first formed under the conditions of a cooling globe?

The answer to this question is simple. The most stable compounds would come first, and they are such as appear among the products of the electric furnace. Carbides, silicides, phosphides, borides, and nitrides are all stable at very high temperatures, and such compounds with iron, nickel, or manganese as bases are substances of high specific gravity and would be likely to sink deeply into the cooling mass. At the surface of the Earth and probably throughout the lithosphere they would cease to exist, for water, especially in the form of superheated steam, transforms them into other compounds, such as hydrocarbons, oxides, silicates, phosphates, borates, and salts of ammonium. Water must have been a compound to appear at an early stage in the process of evolution, and it is one of the principal reagents that were and are active in determining the composition of the Earth's crust.

This speculation, which is not extravagant, receives some support from the study of volcanic emanations, of which carbon dioxide and ammonium chloride are common constituents. Hydrocarbons in small amount are also found among volcanic ejectamenta. The existence of boron nitride within the Earth is suggested by the association of boric acid and ammonium compounds in the Tuscan fumaroles and at other well-known localities. Boron nitride is a very stable compound; but when heated in a current of steam it yields boric acid and ammonia. As for silicates and oxides, they are the chief constituents of the lithosphere. The silicates would be easily formed by oxidation of the primary silicides, but only the simpler compounds, such as constitute at least nine-tenths of the present lithosphere, would appear at first. Their crystallization and segregation could take place only in the cooling of a fused magma. On this point their artificial syntheses are conclusive. From such a magma the primitive crust of the Earth was formed.

A variety of processes, some physical and some chemical, must have taken part in the solidification of the planet; but their effects could hardly have been symmetrically distributed. The temperature of the cooling mass was certainly not uniform. Whenever new compounds were formed heat was generated, the local temperature rose, and inequalities of composition were brought about by diffusion. Where the temperature at the surface of the globe was lowest there solidification began. At such points new chemical reactions became possible through contact with the gases and vapors of the primeval atmosphere. Just what the composition of that atmosphere may have been we do not know; but it must have contained oxygen, carbonic acid, and water, three powerful reagents, with possibly some of the stronger acids also.

Throughout the cooling process and indeed throughout the process of evolution from nebula to planet, gravitational energy was at work distributing the various forms of matter according to their density. In the Earth we have a heavy, probably metallic nucleus, surrounded by a zone of the denser silicates grading upward into lighter compounds, and after them a relatively thin shell of sediments and other decomposition products. Then comes the hydrosphere, and surrounding all the atmosphere. These zones are of course not sharply separated but interpenetrate one another to a greater or less extent. Volcanic effusions, for example, break through the sediments, and locally reverse the primary gravitational arrangement, which, after all, is what might be called an irregular regularity. The broad outlines of the process are clearly discernible in spite of local blurring.

This zonal structure of our planet, due to gravitational adjustment, has been of great significance in fixing the conditions upon which terrestrial compounds could be formed. It is commonly supposed that the Earth is analogous to a huge meteorite, having a nucleus consisting principally of nickel-iron with some inclusions of free carbon and a few simple compounds. This supposition will be considered in detail in the next section of this memoir; if it is correct then the nucleus of the

Earth, or centrosphere, is essentially a region of almost no chemical activity. It is protected from the outermost zones of active reagents by the intervening shells of igneous silicate rocks, which are easily modified by aqueous and atmospheric agencies and in less degree by volcanism. To cite two familiar examples of such changes magnesian rocks are converted into talc and serpentine, and feldspathic rocks are kaolinized. In short, on passing from the centrosphere to the surface of the lithosphere, the chemical changes become more and more varied and complex. Through them the sedimentary rocks were formed, and in the later stages of the Earth's history living organisms also played an important part in the production of limestone, dolomite, and marine phosphates. Leaving minor details out of account we may say that the general conditions governing the evolution of natural inorganic compounds seem to be fairly well understood, even though we know very little of the inner mechanism of the many reactions in which combinations and decompositions proceeded simultaneously. In the geologic history of the Earth's crust the more important of the chemical changes are easily traced. The artificial syntheses of many minerals also give us much information upon the problem of inorganic evolution.

At the surface of the Earth, when its crust was sufficiently cool, the evolution of compounds entered upon a new field of activity. Organic compounds were formed, and they furnished the material basis for the evolution of living beings. Organisms, each capable of reproducing its kind, became physically possible. This faculty of reproduction is something that sharply distinguishes living from nonliving matter.

The probability that carbides and nitrides were among the earliest compounds to form in a cooling globe has already been pointed out, and also that these compounds, by hydrolysis, yield hydrocarbons and ammonia. Calcium carbide yields acetylene, which easily polymerizes into benzene, from which a long list of other hydrocarbons can be derived. The carbides of aluminum, glucinum, and manganese give methane, CH_4; those of the rare-earth metals yield mixtures of acetylene, methane, and ethylene, and from some of them liquid and solid hydrocarbons are also derived. From uranium carbide Moissan[12] obtained a mixture of liquids, consisting largely of olefines with some members of the acetylene series and some saturated compounds. Hydrogen is also set free in some of these reactions.[13]

If now, by reactions such as have just been described, hydrocarbons and ammonia were formed from compounds contained in the primitive magma, a first step was probably taken toward preparing the surface of the Earth for the advent of living organisms. From metallic phosphides phosphine, the analogue of ammonia, would be generated, and it would quickly be oxidized, yielding phosphates. Among the substances that appear in volcanic emanations there are hydrogen sulphide, sulphur dioxide, carbonic acid, and hydrochloric acid, compounds which might all be formed simultaneously with the hydrocarbons. Add to these the gases of the atmosphere, and we shall have assembled much of the raw material that is essential to the later upbuilding of organic tissue. But between magma and protoplasm there is a vast gap, which science has not yet bridged. The evolution of compounds has not stopped, but our knowledge of its course is interrupted.

The moment we enter the field of biochemistry we encounter problems of great complexity. Innumerable new compounds appear, especially in the tissues of plants, and some of them are extremely complicated. Many of these compounds, however, can be isolated and analyzed. We can determine their composition and measure their physical properties, but how they were developed in the growing plant is a question that is rarely answered even in part. One group of examples will serve to show how complex the problems really are.

One of the most marvelous of chemical laboratories is contained within the seed capsule of the opium poppy, *Papaver somniferum.* In that small inclosure a juice is secreted which when dried, solidifies to that extremely complicated mixture opium. In opium about thirty different compounds have been identified, including more than twenty distinct alka-

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[12] Moissan, H., Compt. Rend., vol. 122, p. 1462, 1896. See also Damiens. M. A., Annales de chimie, 9th ser., vol. 10, p. 137, 1918, on the carbides of the cerium group.

[13] For a summary of the literature relating to the inorganic syntheses of hydrocarbons, and especially from the carbides contained in cast iron, see Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 730–732, 1920.

loids, of which morphine, $C_{17}H_{19}NO_3$, is the most abundant but not the most complex, although, as we see from its formula, each molecule contains forty atoms. How many protons and how many electrons are there here, and what are they doing?

But this is not all. The capsule also contains the seeds from which other plants can be grown, and in each plant within a single season this complex of chemical syntheses is begun and completed, and so on generation after generation. The seeds are rich in oil but not in alkaloids; it is at the summit of their growth that these very complicated substances appear.

Suppose now that on this same acre of ground with the poppy are sown the seeds of a dozen or more plants. Each one will be, in a certain sense, a synthetic chemist, working out its own special set of reactions. A tobacco plant will form nicotine, mustard will generate an "oil" rich in sulphur, some species will produce hydrocarbons such as terpenes, while others will specialize in forming sugar or starch or strong acids. All are nourished by the same soil, the same water, and the same atmosphere, but each one breeds true to type and never makes a mistake in its chemistry. Does each seed contain some directive principle that guides its germination and growth? To say that the seeds differ in composition, which is quite true, may give a partial answer to this question; but it does not explain the vital factor, the capacity of each plant to reproduce its kind.

Up to a certain point the evolution of compounds within these different plants follows similar lines. All generate the vegetable fiber that is, so to speak, the fabric of their skeletons, and all produce chlorophyll, the principal coloring matter of their leaves. I use the term chlorophyll in its general sense, although this substance is usually if not always commingled with other compounds of similar character. Here a new reagent becomes of supreme influence—namely, radiant energy, the energy of the Sun's rays. It is only by means of this reagent that chlorophyll can form. Are some of the other syntheses also dependent upon it? Albuminoids and proteids are also produced, and in these colloid substances chemical complexity probably reaches its limit. They are the essential constituents of protoplasm.

In animal matter, which consists almost entirely of proteids, the complexity is even greater than in plants. Plants may contain a much larger number and variety of definite crystallizable compounds, but in animal tissues the proteids predominate, and they are of many different kinds. Into this subject I can not go at length, but I may be permitted to ask one question. Is the morphological or structural increase in complexity from the lowest to the highest forms of life accompanied by a corresponding change in the complexity of chemical constitution? This aspect of evolution has, I think, never been seriously considered, but it surely deserves attention. To show its significance I venture to offer the following illustration, which is based upon an elaborate study of the inorganic matter of marine invertebrates:[14]

In some of the lowest forms of life, as in the diatoms, radiolarians, and siliceous sponges, the skeletal matter consists chiefly of opaline silica, a very simple substance. The stony corals are built up from calcium carbonate, which is slightly more complex. The echinoderm skeletons also contain magnesium carbonate, and the shells of some brachiopods consist mainly of calcium phosphate. The shells of the higher crustaceans, such as the lobster, are still more complicated. With a large proportion of organic matter, proteid in character, they contain both carbonates and phosphates of calcium and magnesium. The progressive increase in complexity is clearly evident. It also appears in the bones of the higher mammals. In them we find organic substances, such as gelatin and fats, but also carbonates of calcium and magnesium, with a very large proportion of calcium fluophosphate. The question that was asked in the preceding paragraph is surely pertinent, and it receives the beginning of an answer here. A complete answer, however, will involve some serious discriminations, and it must also recognize the fact that we are now considering products and not processes. The two fields of investigation must, of course, be studied together, but the distinction between them is clear. A physiological process is a complex of chemical combinations and decompositions, of evolu-

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[14] See Clarke, F. W., and Wheeler, W. C., U. S. Geol. Survey Prof. Paper 124, 1922.

tions and devolutions, and the two sets of phenomena are quite distinct, even though they always appear together. The one is the complement of the other. The physiological processes of the higher animals are surely more complicated than those of lower forms.

For example: In respiration we inhale oxygen and exhale carbonic acid, which is produced by the consumption of organic tissue. The formation and renewal of the tissue is a case of true evolution, to which our question properly relates; the rejected waste or excretory products can for present purposes be disregarded. We are considering the products of growth, not those of decay. The discrimination may sometimes be difficult, but it should never be ignored. The alkaloids of opium, for instance, are waste products and represent the downward path of chemical change. Their citation here, however, serves to illustrate the wonderful complexity of the processes that are involved in the growth of plants.

The formation of any new compound, whether simple or complex, natural or artificial, is an item in the scheme of chemical evolution. Under natural conditions many well-known compounds are incapable of existence; some are destroyed by even moderately high temperatures; others are decomposed by the action of water; and still others, like the fulminates, are easily exploded by percussion or friction. All these inhibitions are evaded or controlled by a skillful chemist, who can regulate temperatures and pressures and can establish for each compound the environment in which it can form. He can also work with pure materials, which are rarely found under natural conditions. The artificial compounds help us to a better understanding of those which exist in nature, and this can easily be shown.

Many of the minerals that form the solid crust of the Earth have been reproduced synthetically by methods equivalent to those followed by nature. The species that are characteristic of the igneous rocks, such as the feldspars, pyroxenes, and olivine, originate in molten magmas, and artificial magmas yield the same compounds. Quartz may be either magmatic or crystallized from aqueous solutions, and both modes of origin can be copied in the chemical laboratory. Artificial limestone is easily prepared, and so too are gypsum and a nunber of other minerals, all of aqueous origin, that are found in beds of salt. The researches of Van't Hoff and his colleagues upon the Stassfurt salts are especially suggestive. The compounds associated with the salt were not only prepared synthetically, but the temperature at which each one formed was also determined, giving datum points in what has been called a "geological thermometer." Similar temperature relations have been discovered for other minerals, such as the silica group and wollastonite, and they give valuable information as to the conditions under which the rocks containing them were deposited. In short, the chemical processes that took part in terrestrial evolution are being revealed experimentally. The literature of synthetic mineralogy is very voluminous, but these few examples are all that need to be cited here. They serve to illustrate the methods by which some problems of evolution are being solved.

What has been said relative to the syntheses of inorganic compounds also applies, but with serious limitations, in the organic field. Many substances that are found to exist in living organisms have been made artificially, but by methods that are surely not identical with those followed by plant or animal. In life many syntheses are effected simultaneously and rapidly; in the laboratory the conditions are quite different. The chemist starts with pure material and builds his compounds individually and slowly, but his results are nevertheless of great significance, even though they may not be directly applicable to the interpretation of vital phenomena. There is, however, a partial correlation, which is better than none at all.

This is no place for an essay on biochemistry, which may be described as the dynamic side of physiology. All living organisms, considered apart from their psychological relations, are dependent upon a complex of chemical changes, some products of which are utilized and others rejected as waste. In the digestion of food many of these changes have been traced, and a great variety of compounds take part in them. Some of the compounds, especially the proteids, are broken down into simpler forms; and their derivatives are distributed each to its proper place in the organism. The motive power that effects their distribution is thermochemical in origin and is measured in terms of calories. Finally, new proteids are formed, and wasted tissues are regenerated; and this is true chemical evolution. The evolution of the Earth's crust and the evolution of living tissue are parts of the same line of growth from the simplest to the most complicated forms of matter. The line, however, is not straight but one with many branchings.

THE RELATIVE ABUNDANCE OF THE CHEMICAL ELEMENTS.

One of the most obvious facts in chemistry is that some of the elements are very abundant and others extremely rare. It is also easy to see that this distinction is definitely related to the conditions under which the different elements were generated. The simplest and most stable ones were formed at the highest temperatures and in the greatest abundance; the most complex elements appeared last of all and in the smallest quantities. The original nebula was a finite mass of matter, and the scarcer elements represent the material left over after the more common ones had been formed. How far do these conclusions harmonize with the observed facts?

In an attempt to answer this question we must recognize certain limitations. An almost infinitesimal portion of the matter that forms the solar system is all that is available for direct quantitative investigation. Only the Ocean, the atmosphere, and a very thin outer shell of the Earth's crust are accessible to us. As for the Ocean and the atmosphere, their composition is well known; that of the rocky shell is less easily ascertained.

In order to determine the average composition of known terrestrial matter we must first fix the relative proportions of its three components. For this purpose let us assume that the crust of the Earth to a depth of 10 miles is essentially like the average rock of its surface, of the rocks which we know and can analyze. The volume of such a crust, including the mean elevation of the continents above the sea, is 1,633,000,000 cubic miles, with a probable density of about 2.7 to 2.8.

The volume of the Ocean is approximately 302,000,000 cubic miles, although some authorities give slightly higher figures, and its density is a little below 1.03. This is the maximum density found by Dittmar in the water of the great oceans, and its use here makes a liberal allowance for the saline matter, such as beds of salt, that are found in the crust of the Earth. For present purposes they are negligible quantities. If the salts of the Ocean were gathered into one solid block, they would have a volume of at least 4,800,000 cubic miles, or enough to cover the entire United States to a depth of 1.6 miles. The fresh waters of our globe are also negligible, for a quantity equivalent to 1 per cent of the Ocean would cover all the land areas to a depth of 200 feet. Even the mass of Lake Superior becomes relatively insignificant. The mass of the atmosphere, so far as it can be determined, is equivalent to that of 1,268,000 cubic miles of water, the unit of density. Combining these figures, we have for the composition of known terrestrial matter about 93 per cent of solid crust, with 7 per cent for the Ocean. The proportion assignable to the atmosphere is only 0.03 per cent, which may be regarded as a small correction to be applied when needed.[15] We are dealing with the relative abundance of the different forms of matter and not with absolute quantities. Quantitative accuracy is not attainable.

What, now, is the composition of the accessible part of the lithosphere? Neglecting the thin film of organic matter upon its surface, we need only consider two classes of rocks, the igneous and the sedimentary. Metamorphic rocks are merely the result of alterations of one or the other of these two and may be left out of account. Such inclusions as beds of coal or metallic ores are insignificant in quantity as compared with the vast mass of rocks now under consideration, which is, as nearly as can be determined, 95 per cent igneous and 5 per cent sedimentary. The method by which these figures were obtained, together with the average composition of the sediments, I have given elsewhere.[16]

As it is impossible to analyze the 10-mile crust as a whole, we must do as well as we can by the method of sampling—that is, we must take samples of igneous rocks, the parents of the others, from as many different localities as possible, and then average the

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[15] For the details of this computation see Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 22–33, 1920.

[16] Idem, pp. 29–32.

analyses. Thousands of such analyses have been made for petrologic purposes and are now available for use. The material came from all quarters of the globe, and the analyses that are considered trustworthy have been assembled by H. S. Washington in a monumental volume.[17] From the data given by him 5,159 analyses rated as "superior" have been taken and averaged together, giving a fair conception of the mean composition of the igneous rocks.[18]

Now, omitting details, which can be found in the publications already cited, let us consider the significance of the following averages. The first column of figures gives the mean composition of 5,159 igneous rocks, stated in terms of elements and in percentages. The last column gives the average obtained by including accepted values for the sediments, the ocean, and the atmosphere, or in other words the mean composition of all known terrestrial matter to an assumed depth of 10 miles below sea level.

Average composition of igneous rocks and of all known terrestrial matter.

	1	2
Oxygen	46.41	49.19
Silicon	27.58	25.71
Aluminum	8.08	7.50
Iron	5.08	4.68
Calcium	3.61	3.37
Sodium	2.83	2.61
Potassium	2.58	2.38
Magnesium	2.09	1.94
Titanium	.72	.648
Phosphorus	.157	.142
Hydrogen	.129	.872
Manganese	.124	.108
Chlorine	.096	[a].228
Carbon	.051	[b].139
Minor constituents	.463	.473
	100.00	100.000

[a] Oceanic.

[b] In limestone.

These figures show that eight elements form 97.38 per cent of all known terrestrial matter, leaving only 2.62 per cent for all the others. The influence of the Ocean and the atmosphere is very slight, and with a thicker mass of igneous rocks it would be still smaller. In the Earth as a whole the Ocean would amount to only a small fraction of 1 per cent and therefore be negligible.

In many of the published analyses of igneous rocks figures are given showing appreciable but small percentages of some of the scarcer elements. The average amounts are as follows:

Barium	0.081	Nickel	0.031
Sulphur	.080	Fluorine	.030
Chromium	.052	Copper	.010
Zirconium	.051	Lithium	.005
Vanadium	.041	Zinc	.004
Strontium	.034	Lead	.002

Several attempts have been made to determine the composition of the Earth as a whole, all based upon its supposed similarity to a huge meteorite. The mean density of the Earth is nearly double that of its crust, and it behaves like an enormous magnet. Hence the assumption has been made, to which I have already referred, that its central portion is metallic and consists largely of iron. How far is this assumption justifiable?

To answer this question let us begin with the chemical composition of known meteorites. These extraterrestrial bodies are divided into two classes, meteoric stones and meteoric irons, which, however, are not sharply distinct. Nearly all the stony meteorites contain more or less iron, and many of the others contain stone. For instance, the pallasites are masses of iron, with something like the texture of a sponge, in which the cells are filled with nodules of olivine. Again, the meteoric shower that fell at Estherville, Iowa, in 1879, contained masses of stone and many smaller masses of iron. These were all, of course, components of the original meteor. For the average composition of 99 meteoric stones we have the following computation by Merrill.[19] The first column of figures gives the actual average; the second is recalculated to 100 per cent after rejecting the admixed nickel-iron, sulphides, and phosphides.

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[17] Washington, H. S., Chemical analyses of igneous rocks, 1884 to 1913: U. S. Geol. Survey Prof. Paper 99, 1917.

[18] A detailed critical discussion of the method of averaging and the results obtained is to appear in Professional Paper 127 of the Geological Survey, by Clarke and Washington, now in press. An abstract of the averages was published in the Proceedings of the National Academy of Sciences for May, 1922.

[19] Merrill, G. P., Am. Jour. Sci., 4th ser., vol. 27, p. 469, 1909. Another average, by O. C. Farrington, appears in Field Columbian Mus. Pub. 151, 1911. It is in fair agreement with Merrill's.

Average composition of meteoric stones.

	Found.	Recalculated.
Silica	38. 98	45. 46
Alumina	2. 75	3. 21
Ferrous oxide	16. 54	19. 29
Lime	1. 77	2. 06
Magnesia	23. 03	26. 86
Soda	. 95	1. 11
Potassa	. 33	. 38
Manganese oxide	. 56	. 65
Chromite	. 84	. 98
Nickel, including cobalt	1. 32	....
Metallic iron	11. 61	....
Sulphur	1. 85	....
Phosphorus	. 11	....
	100. 64	100. 00

Some of the analyses show small amounts of copper, tin, carbon, etc., which need not be considered here. The average stone is essentially a peridotite and therefore quite different from the average terrestrial rock. A great deficiency in feldspars is evident, and they form nearly 60 per cent of the 10-mile shell of the lithosphere. There is little or no free silica indicated by the figures. That the meteorites were originally in a state of fusion is also clear, for the dominant mineral, olivine, is formed only in that way. The same is true also of the glass, which is a common constituent of meteoric stones.

It is by no means certain that the average given in the foregoing table represents with any accuracy the mean composition of all known meteoric stones, of which many were never analyzed. Even these meteorites form but a trifling fraction of the vast number that must have fallen unseen. Some doubtless fell in the ocean, and others in deserts or forests, never to be found. Nevertheless the average is not without value, when it is considered in relation to other data. As for the individual stones that are represented in the average, they show great differences in composition. A very few, of which Juvinas and Stannern are typical, consist mainly of augite and anorthite, with very little nickel-iron. The Bishopville stone is nearly pure enstatite. These stones are exceptional; in by far the greater number of known falls pyroxenes and olivine are the dominant minerals, with variable proportions of nickel-iron. The transition from stone to iron is very gradual. The very common chromite of meteoric stones is invariably associated with magnesian minerals, iron, and nickel—the same association that is found in terrestrial rocks. Oldhamite, calcium sulphide, is only known as a meteoric mineral; it dissolves in water and rapidly hydrolyzes, therefore it can not long exist except in anhydrous surroundings, and all our igneous rocks contain small amounts of water.

One very small group of meteoric stones deserves to be considered separately—the carbonaceous meteorites. The type and extreme example of these is the one that fell at Orgueil, France, in which Pisani found 13.89 per cent of water plus organic matter, which consisted essentially of hydrocarbons. Such a meteorite could reach the surface of the Earth only under very exceptional conditions. The chances are that its organic matter would be burned soon after it entered the atmosphere, and its stony portion disintegrated and scattered as dust. If so the atmosphere must receive accessions of carbon dioxide that would have a distinct influence upon plant life and would perhaps account, in part at least, for the carbon that is locked up in coal and petroleum. This, I admit, is pure speculation, but not without some plausibility. A cometary origin of these meteors is probable, for hydrocarbons are shown in the spectra of comets, and several instances are known of periodic showers of stars that have followed the paths of periodic comets which have disappeared. Biela's comet is one which after repeated returns is now represented only by a starry shower. We can not, however, assume that all meteors are the remains of comets. There is, as will be seen later, strong evidence to the contrary.

The average composition of meteoric iron is more easily determined than that of meteoric stone. The one consists mainly of an alloy of nickel and iron; the other is a mixture of different silicates. The irons contain, in minor proportions, several other substances, such as troilite, FeS; schreibersite, a phosphide of iron and nickel; daubréelite, $FeCr_2S_4$, the sulphide corresponding to the chromite of meteoric stones; lawrencite, $FeCl_2$; cohenite, $(FeNiCo)_3C$; graphitic carbon; and in the iron of Canyon Diablo, minute diamonds. Diamond is also found in the meteoric stone of Novo Urei. Carborundum, CSi, is also reported by Moissan as present in the Canyon Diablo iron. Nodules of troilite and of graphitic carbon are common, some of them as large as a hen's egg; the other inclusions are diffused in smaller amounts. Of these the lawrencite is in one way the most conspicuous, although it is rarely seen in distinct masses. On exposure to moisture it is hydrolyzed, forming basic chlorides and releasing hydrochloric acid, so that its presence is too often manifested by the tendency of an iron to rust and ultimately to fall to pieces. Everyone who has had much experience in handling collections of meteorites knows how troublesome this obnoxious compound is. It is very difficult to stop its ravages. It is not improbable that much of the chlorine in the ocean came originally from lawrencite. Was the primeval ocean strongly acid? The question is legitimate, even if it can not be definitely answered. Some of the oceanic chlorine is undoubtedly of volcanic origin, and that may have had its source in lawrencite. We do not know the facts but may be permitted to suppose. One thing is certain—namely, that the permanence of a meteoric iron depends upon the amount of ferrous chloride which it contains.

At Ovifak, in Greenland, and at several neighboring localities, native iron is found which was at first thought to be of meteoric origin. It is now known to be terrestrial iron, brought up in some manner from below, together with the basalt in which it is embedded. Some of it is in small grains and some in large masses of several tons in weight, and it resembles meteoric iron in every essential particular. It contains some lawrencite, and also carbon, which is combined with iron, probably as cohenite. The presence of a carbide was proved by George Steiger in the laboratory of the United States Geological Survey. By heating some of the Ovifak iron with ammonium chloride he obtained a mixture of hydrocarbons, both saturated and unsaturated.

For the average composition of meteoric iron and its terrestrial equivalent we now have the following data: First, the average of 318 analyses of meteoric iron, as computed by Farrington[20]; second, the average of 13 analyses of the Greenland iron, cited by Dana.[21] In the analyses of Greenland iron figures for silica and insoluble matter have been rejected as representing impurities taken up from the adjacent rocks.

Average composition of meteoric and native iron.

	Meteoric.	Terrestrial.
Iron	90.85	92.53
Nickel	8.52	2.20
Cobalt	.59	.62
Copper	.02	.23
Sulphur	.04	.28
Carbon	.03	1.78
Phosphorus	.17	.21
Chlorine	....	.06
Chromium	.01	....
	100.23	97.91

These averages, although they differ somewhat, do so no more than individual analyses of meteoric iron. No two irons are precisely alike. The absence of chlorine from the first column of figures merely means that it was not determined, and the same is true with reference to chromium in the second column. Analyses of rocks and minerals differ widely as regards completeness.

In one way the analyses of meteoric irons are likely to be slightly misleading. They represent clean, bright samples of the nickel-iron and take no account of the large inclusions of graphite, troilite, and the more generally diffused ferrous chloride. The composition of the entire mass of an iron would be unlike that of the selected metal, and the inclusions might amount to several per cent. No good estimate can be made of their average quantities. The averages given in the table, therefore, represent only approximate orders of magnitude, but the percentages of the minor constituents are certainly not large.

That the minerals of the meteoric stones were originally in a state of fusion seems to be clear. Was the meteoric iron also molten? This question can be answered in the affirmative, for the following reasons:

In the preceding section of this paper it was shown that carbides and phosphides were among the compounds that would be the earliest to form in a cooling globe. Both carbides and phosphides are found in meteoric iron, and the even more significant sulphides also. Furthermore, troilite and graphitic carbon are often found in large nodules that could

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[20] Op. cit.

[21] System of mineralogy, 6th ed., pp. 28, 29, 1914.

hardly have segregated except from a fluid or semifluid mass. The diamonds of the Canyon Diablo iron tell the same story. The artificial diamonds obtained by Moissan were produced by dissolving carbon in molten iron and cooling under great pressure. Finally, the highly crystalline structure of meteoric iron points to the same conclusion. No artificial iron shows that peculiarity. All the evidence points in one direction, and the similarity of origin of stones and irons seems to be almost beyond doubt. Both stones and iron were formed in a cooling globe which in structure resembled the cooling Earth. This theory as to the origin of meteorites is the only one that is supported by positive evidence; all others are purely speculative. The theory is not original with me. It was advocated by Meunier and others and has since been fully discussed by Farrington,[22] who has made use of much the same evidence as I have cited here. He also calls attention to the fact that meteoric stones sometimes show indication of strains and of brecciated structure, similar to corresponding features that are common in the crust of the Earth. Farrington's arguments in support of his thesis seem to be incontestable.

The lines of evidence used by Farrington in his argument have recently been made much stronger by the study of a meteoric stone that fell at Cumberland Falls, Ky., on April 9, 1919. This stone, which has been thoroughly investigated by Merrill,[23] is made up of two distinct types of meteorites. The larger part is white and consists mainly of enstatite with a little diallage. It contains, however, inclusions of a black stone, made up of olivine and enstatite. There are also some scales of graphite, with a very little nickel-iron and troilite. The most noteworthy feature of the stone is that the white portion, instead of being comparatively homogeneous, is a breccia, a mass of sharply angular fragments, which could be formed only by crushing the rock under great pressure or by grinding. The only interpretation that can be given to these facts is that the meteorite is a fragment of a much larger mass, of what may be called subplanetary dimensions—one large enough for the same processes to operate that are recognized in the rocks of the Earth. How and when that planetoid was disrupted we do not know, and speculation upon that subject would be out of place in this paper.[24] Its chemical composition, however, as shown by the analyses of meteorites, must have closely resembled that of the Earth.

To complete the analogy between the Earth and the broken planetoid we should be able to calculate the percentage composition of the latter. This, however, can not be done, for much of the meteoric matter is lost. In the catastrophe that destroyed the planetoid its lighter, outer shell was probably scattered in dust, or in fragments so small that few of them, even if they reach the Earth, could ever be collected and identified. No granitic meteorite has yet been found, and the only distinctly feldspathic meteorites are those of the Juvinas and Stannern types, in which the feldspar is anorthite. Alkali feldspars occur in meteorites in very small and relatively unimportant proportions.

The suggestion that the outermost portion of the planetoid was lost is not altogether imaginative. It is supported by the well-known phenomena that attend the fall of a large meteor. These are a brilliant light and a violent explosion, with a noise which has been compared to thunder or the firing of heavy artillery. The meteor is also followed by a train of sparks as seen by night, or one of "smoke" in daytime. An explanation of these phenomena was put forth by Maskelyne[25] in 1862, about as follows: The meteor, coming from the cold of outer space, enters the atmosphere of the Earth with something like planetary velocity. By atmospheric friction its surface is almost instantly heated to incandescence; this portion of course expands and breaks away from the central mass with explosive violence. In this way the meteor is disrupted, and the fragments that are thrown off are seen in the trail of sparks or smoke which follows the falling mass. This explanation of the phenomena is very simple and seems to be satisfactory. The meteoric stone has just the composition which would result from the process described above. Its lighter surface has been blown away, and only the denser, interior portion of different composition has fallen to the ground.

So far the evidence seems to be conclusive that the meteorites are fragments of a mass of

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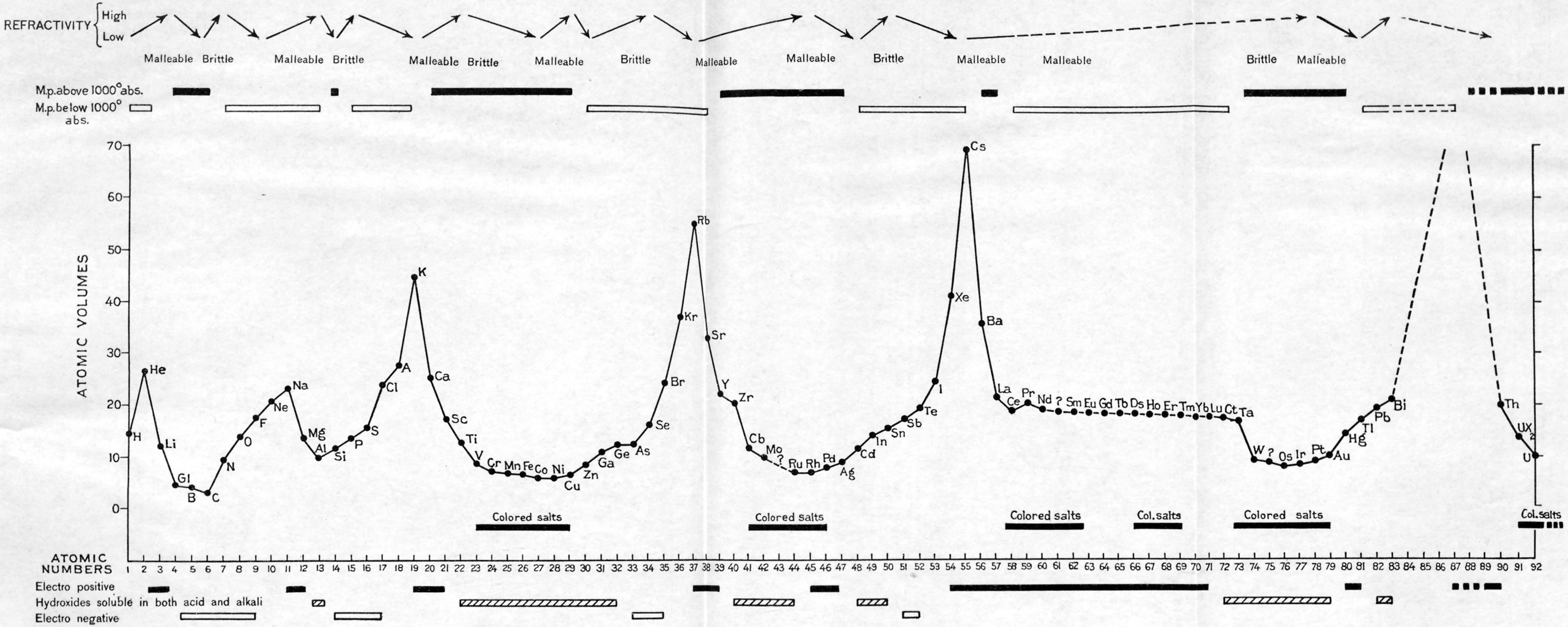
[22] Farrington, O. C., Jour. Geology, vol. 9, p. 630, 1901.

[23] Merrill, G. P., U. S. Nat. Mus. Proc., vol. 52, p. 97, 1920.

[24] T. C. Chamberlin (Jour. Geology, vol. 9, p. 370, 1901), regards meteorites as fragments of a planetoid which was torn to pieces by near approach to a larger mass.

[25] Maskelyne, N. S., British Assoc. Adv. Sci. Ann. Rept., 1862, pt. 2, p. 188.



THE CURVE OF ATOMIC VOLUMES.

matter which in composition closely resembled the Earth. Of the dimensions of that mass we know nothing, except that it must have been large enough to maintain its integrity at first in a fluid state, and that after it had solidified crustal movements occurred which produced the peculiar structures of meteoric stones. Its disruption took place long ago, how long we can not say; and many, perhaps the greatest number, of its fragments reached the Earth shortly after the catastrophe. Of course we can not assume that there was only one such mass; there may have been more than one, but that question is not germane to the present discussion. The known meteorites show clear indications of a common origin; whether from one or two planetoids we need not ask.

From what has been said so far, it is clear that the Earth was once a fluid mass, in which as it cooled the iron separated from the silicates just as it does from the slag in a blast furnace. The solid Earth, then, consists of two components—a nucleus of metallic nickel-iron and an envelope of silicate rocks. This conclusion is by no means new. It has been adopted by many other writers, and especially by Wiechert,[26] whose argument is based on geodetic data. For the composition of the nucleus we have Farrington's average of 318 analyses of meteoric iron, which, however, is subject to correction for its inclusion of other substances. What, now, is the average composition of the lithosphere?

For the composition of the lithosphere we have that of the igneous rocks near its surface and that of the stony meteorites, which are supposed to represent the material closest to the central iron. Between the two, the top and bottom of the lithosphere, there is a wide gap, which can be filled only hypothetically—that is, by making probable or at least plausible assumptions. In the first place we may assume that between the lighter rocks at the surface and the heavier at the bottom there is a fairly regular gradation, from an average andesite above to a peridotite below. In this hypothesis an average basalt may be assumed to fill the gap, without much risk of serious error. For the composition of the basalt we may use the average of 161 analyses as computed by Daly,[27] but reduced here to elementary form. For the mean composition of the lithosphere there are, then, three averages to be combined, as follows: First, the average for the surface rocks; second, that of the basalt; and third, that of the meteoric stones as given by Merrill. In this combination the minor constituents are discarded, as representing small corrections that can be applied when it is desirable to do so. The incompleteness of the meteorite analyses renders the omission necessary. The three sets of figures, given equal weight, appear in the following table, together with their mean, the composition of the lithosphere.

Average composition of the lithosphere.

	Surface rocks.	Basalt.	Meteoric stone.	The lithosphere.
Oxygen	46.72	44.28	42.16	44.38
Silicon	27.76	23.27	21.21	24.08
Aluminum	8.13	8.44	1.70	6.09
Iron	5.12	8.87	15.25	9.75
Magnesium	2.10	3.76	16.12	7.33
Calcium	3.64	6.49	1.48	3.87
Sodium	2.86	2.34	.82	2.01
Potassium	2.60	1.28	.31	1.39
Titanium	.73	.83	....	.52
Manganese	.12	25	.50	.29
Phosphorus	.16	.19	....	.12
Chromium	.06	....	.45	.17
	100.00	100.00	100.00	100.00

It will be noticed that in this average the nickel-iron of the meteoric stones does not appear. It is included in the total amount of metal which is required to bring the density of the Earth up to 5.5.

Here we may venture to use a curious analogy to which Wiechert has called attention.[28] Astronomers are generally agreed that the Moon was originally thrown off from the Earth. If so, its composition should be essentially like that of the lithosphere. Its mean density, 3.34, is that of some meteoritic olivines. That density, however, is too high for the stony portion of the lithosphere and suggests that the Moon contains, like the meteoric stones, some nickel-iron. The average meteoric stone, according to Merrill's calculation, contains nearly 15 per cent of nickel-iron, sulphides, and phosphides. The average density of 78 meteoric stones, as computed by me, is 3.54, a value that fits in well with the figures given above.

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[26] Wiechert, E., Gesell. Wiss. Göttingen Nachr., 1897, p. 221.

[27] Daly, R. A., Am. Acad. Proc., vol. 45, p. 211, 1910.

[28] Wiechert, E., Deutsche Rundschau, vol. 132, p. 376, 1907. English translation in Smithsonian Inst. Ann. Rept., 1908, p. 431.

To the stony matter alone of the lithosphere a probable density of 3.2 may reasonably be assigned.[29] That of the surface crust is about 2.8. For the density of the metallic nucleus the figure 7.8 is commonly assumed, but it may be a trifle too high. No allowance is made for inclusions of lighter material, but a density of 7.7 would probably be a minimum. The mean density of the Earth, as given by different authorities, lies somewhere between 5.5 and 5.6.

With the data now at hand we can compute, at least approximately, the composition of the Earth as a whole and the relative abundance of the elements in the solar system. Wiechert[30] has already shown that the iron nucleus of the Earth and its rocky envelope are roughly equal in volume. If we assign to the Earth and its two components the respective densities of 5.5, 7.8, and 3.2 this relation holds exactly, and no probable changes in these values will greatly modify Wiechert's conclusion. Whatever permissible values we assign to the densities the two volumes will approach equality. The variations will not exceed 3 per cent in either direction—that is, for a little more iron and a little less rock, or vice versa. From the volumes and the densities the relative masses of the two components of the Earth can be determined, and then Farrington's average composition of meteoric iron and that of the lithosphere can be combined together. This combination has already been attempted by Farrington,[31] but with the three densities taken as 5.57, 7.8, and 2.8. Here the figure for the density of the Earth is probably too high, and that of the lithosphere certainly too low. For the composition of the Earth by weight they give 73.6 per cent of free metals and 26.4 per cent of rock. With the densities 5.5, 7.8, and 3.2 the percentages become 70.75 and 29.25, respectively. Considered as representing orders of magnitude, and we can expect nothing more, these two estimates are not very far apart. In the following combination the two percentages are rounded off to 71 and 29. Farrington's combination, however, differs from ours not only in the assumed densities but also in assigning to the composition of the lithosphere that of its 10-mile crust. The two combinations are not comparable.

Average composition of the Earth.

	Nickel-iron (71 per cent.)	Lithosphere (29 per cent.)	The Earth (100 per cent).
Oxygen		44.38	12.77
Silicon		24.08	6.98
Aluminum		6.09	1.86
Iron	90.64	9.75	67.20
Nickel	8.51		6.04
Cobalt	.58		.41
Magnesium		7.33	2.13
Calcium		3.87	1.12
Sodium		2.01	.58
Potassium		1.39	.39
Titanium		.52	.15
Manganese		.29	.08
Phosphorus	.17	.12	.16
Chromium	.01	.17	.07
Sulphur, carbon, copper	.09	(?)	.06
	100.00	100.00	100.00

It needs no argument to show that these figures have no claim to anything like finality and that their value depends upon the assumptions that underlie the calculations. The fundamental assumption, which rests upon pretty definite evidence, is that the original mass of which the meteorites are fragments was similar in composition to the Earth and was formed in the same way.

The second assumption, that the Earth contains a nucleus composed mainly of nickel-iron, surrounded by a stony envelope, is sustained by the facts that the Earth behaves like a huge magnet and that its mean density is about double that of the surface rocks. The application of these facts to the problem in hand involves subordinate assumptions as to the relative densities of the nucleus and the lithosphere. No probable change in the figures assigned to these densities can make any great change in the orders of magnitude as given in the table. The relative order of abundance will be the same, with iron first, oxygen second, silicon third, and so on. As for the scarcer elements, those which do not appear in the table, their total amount can not much exceed 1 per cent, and their inclusion would make only insignificant changes in the percentages assigned to the really abundant substances. After making all reasonable allowances for the scarcer elements, we can say that ten of the more abundant ones, all below 60 in atomic weight, make up at least 99 per cent of all terrestrial matter. They are among the simplest and therefore the most stable elements and were formed in the largest quantities.

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[29] Wiechert (op. cit., 1907), gives a density of 3.4. In his earlier paper he adopts the value 3.2.

[30] Wiechert, E., Gesell. Wiss. Göttingen Nachr., 1897, p. 243.

[31] Farrington, O. C., Field Columbian Mus. Pub. 151, 1911.

This rule, as has been shown already, is revealed by the evidence furnished by the stellar spectra.

Whether all the members of the Solar System are precisely alike in composition is and must remain a matter of conjecture. It is conceivable that the outer planets may be somewhat richer than the Earth in the lighter elements, such as aluminum, magnesium, calcium, and the alkali metals. On the other hand, the Sun may be richer in iron. If that supposition is correct, then the inner planets should approximate an average composition and represent the entire system. This hypothesis, of course, can neither be proved nor disproved. Definite evidence is lacking.

From the analyses of meteoric stones we can obtain some additional suggestions as to the distribution of matter within the Earth. In one of Farrington's papers,[32] which I have already cited, he has tabulated 125 analyses of meteoric stones, classified according to the quantitative system. One analysis falls in the salfemic class, 9 are dofemic, and 94 perfemic. The classes persalane and dosalane are entirely missing, for they belong to the destroyed surface of the wrecked planetoid. Now, these analyses show a distinct gradation in the amounts of nickel-iron which the stones contain. The few feldspathic meteorites, those that were nearest the surface of the parent mass, contain little or no nickel-iron, which increases with some regularity to the end of the perfemic series. The regularity is not sharp and might better be described as a tendency, for the following reasons:

In a single meteorite of large size the nickel-iron is not uniformly distributed, and the analyses were made on small fragments of not more than a few grams in weight. Adjacent fragments might have been either richer or poorer in nickel-iron than those which were analyzed. To analyze a complete stone is never practicable, nor is it feasible to sample a meteorite as one would sample an igneous rock or a carload of ore. These considerations amply account for the irregularities shown by the analyses. In spite of these difficulties the tendency toward a definite arrangement of the meteorites seems to be fairly clear. If they really represent a planetoid that originally resembled a small Earth, the distribution of matter within the Earth as set forth below is highly probable.

At the center of our planet we should have a rather ragged spheroid, with no well-defined margin, consisting mainly of nickel-iron. Near its surface the metal would assume the pallasite type and begin to show inclusions of stony matter, principally olivine. This material would gradually shade into silicate rocks containing large inclusions of free metal, and so on, step by step, until the lighter feldspathic rocks began to appear. These rocks, as the analyses show, contain little or no nickel-iron, and that present occurs in very small, sometimes almost imperceptible grains. The condition thus outlined is exactly what we should expect to result from the slow cooling of a molten globe. The heavier substances should gravitate to the center, followed in order of density by the lighter substances. The evidence at our disposal seems to warrant the conclusions drawn from it. We are dealing, however, with probabilities, not with proofs.

From the evidence presented in the preceding pages some additional conclusions may be drawn. If the Earth consists of a solid nucleus of nickel-iron, surrounded by an envelope of silicate rocks in equal proportions by volume, what is the diameter of the one and the thickness of the other? For the sake of simplicity we may assume ideal conditions, as follows: All the iron is supposed to be concentrated in the form of a perfectly smooth sphere, in uniform contact with its envelope. The volume of the Earth, as generally accepted, is 259,886,000,000 cubic miles. This corresponds to a nuclear diameter of 6,284 miles and a radius of 3,142 miles. Subtracting this figure from the mean radius of the Earth, 3,959 miles, we get 817 miles as the average thickness of the ideal lithosphere. This, however, is only a first approximation to reality, and at least one correction to it is possible.

In calculating the average composition of the lithosphere one-third of it was assumed to be equivalent to an average meteoric stone, but with one qualification. The disseminated nickel-iron, sulphides, and phosphides were withdrawn from the stone and added to the nucleus, making it too large and the true lithosphere too small. The equality of volume as given between nucleus and envelope is really that between the metallic (or rather meteoric) iron and the silicate rocks.

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[32] Farrington, O. C., Field Columbian Mus. Pub. 151, 1911.

The metallic inclusions in the average meteoric stone amount to a little under 15 per cent by weight, and even less by volume. An addition of 5 per cent to the volume of the lithosphere, and a corresponding reduction to the nucleus of the Earth, only lowers the diameter of the nucleus to 6,192 miles and raises the thickness of the lithosphere to 863 miles. This is probably a maximum correction, but any attempt at a greater refinement of the figures would be useless. Absolute accuracy is unattainable, for there is no sharp dividing line between the two components of the Earth. Furthermore, all the data which have been used in the calculations, even those relative to the volume of the Earth and its density, are subject to corrections of undetermined magnitude and direction. There is, nevertheless, a strong probability that the diameter of the nucleus is of the order of 6,200 miles and that the thickness of its envelope is less than 900 miles. Similar figures have been obtained by Wiechert,[33] who assigns to the nucleus a diameter of 10,000 kilometers, or 6,214 miles, to which a thickness of its envelope of 855 miles corresponds. Wiechert's results and mine were reached by entirely different methods, and their close agreement is therefore very satisfactory. Gutenberg,[34] however, from a study of earthquake waves, gives the nucleus of the Earth a radius of only 3,500 kilometers, or 2,175 miles. The corresponding thickness of the lithosphere is 1,784 miles, or double the value found in this investigation. It is for some geodesist to explain this discrepancy.

Up to this point the vexed questions of pressures and temperatures within the Earth have not been considered. On the one hand it has been commonly assumed that because of increasing pressure the densities from the surface to the center of the Earth must have steadily increased, and a similar assumption has been made with regard to temperatures. But here we have two opposing forces, one tending to increase, the other to diminish volumes. Whether these forces balance or not is a question which needs more consideration than I can give it. In its investigation many factors, hitherto generally neglected, have to be taken into account. The Earth is not a homogeneous body. It is made up of many different substances, which are unlike in composition, in density, in fusibility, in specific heat, in conductivity, and in compressibility. Furthermore, we must determine whether compressibility is a limited property of matter or whether it can go on indefinitely. It is also necessary to consider the comparatively abrupt change from the envelope of silicate rocks to a nucleus of metallic iron, which seems to be sustained by strong evidence. The rocky shell of the Earth is more compressible than its metallic interior. Anything like a regular increase of density within the Earth because of an assumed increase of pressure is highly improbable. Unlimited compressibility would end in zero volume, which is absurd. There must be a limit somewhere, where pressure and the resistance to pressure exactly balance, and that limit may have been reached in the metallic nucleus of the Earth, an inference which is suggested by the rigidity of our planet. If it has not been reached then the volume of the Earth must be slowly shrinking, but of that there are no clear indications.

The assumption that temperatures within the Earth increase regularly with the depth is based upon a very short range of observations. In deep wells and other borings the temperature increases, but not to the same extent in all localities, the average amount being about 1° F. in 60 feet. The actual measurements are limited to depths of only a little more than a mile, and by extrapolation the conclusion has been reached that at the center of the Earth the temperature must be high enough to surpass the critical temperatures of all known substances. The temperature of the Sun, which is now well fixed as something like 6,000° C., would thus be exceeded many times over. Extrapolation sometimes leads to very surprising conclusions.

Let us now consider the heat of the Earth under two distinct headings—namely, residual or original heat and new heat such as is constantly being generated. By residual heat is meant that which was retained by the cooling Earth within its interior, mainly in its nucleus and to a less degree in the lithosphere. At and near the surface of the Earth the new heat becomes evident as the result of chemical activity, friction, and several other causes. The heat derived from radium, as shown by

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[33] Gesell. Wiss. Gottingen Nachr., 1897, p. 243.

[34] Gutenberg, B., idem, 1914, p. 176.

the radioactivity of the rocks, has in recent years received much consideration, but its importance may have been exaggerated. It is, however, not negligible. That due to the impact of meteorites is relatively insignificant.

That chemical changes are constantly taking place in the crust of the Earth is a matter of common observation, and each one has definite thermal significance. Some reactions are exothermic and others are endothermic, but whether these gains or losses of heat balance or one or the other predominates is difficult and perhaps impossible to determine. Rocks are decomposed by the joint action of air and water, and heat is both gained and lost in the rather complex processes. The intensity of the reactions is greatest, of course, in humid areas and least in desert regions; it can not be the same for all localities. To discuss this question at length would hardly be justifiable in a paper of this kind: it is enough to show that the question deserves consideration. Even the heat emitted by volcanoes is in part, if only a small part, of chemical origin. The heat of some coal mines and of mines in which sulphide ores are worked is due to oxidation. Examples like these might be multiplied indefinitely. In many of the changes solar radiations also take part, and energy that may be released later is stored up within the Earth.

The crust of the Earth is constantly in motion, and every movement is accompanied by friction. The slightest tremor generates its share of heat, and its aggregate amount must be enormous. Mountains are raised to great elevations; rocky strata are folded, bent, broken, or distorted; there are landslides and all the varieties of erosion; and every one of these movements, great or small, is a source of what I have called new heat. Even volcanic heat is partly and perhaps largely due to friction. Volcanoes, as a rule, are situated along lines of weakness in the crust of the Earth, where earthquakes (and consequently friction) are most common.

All or nearly all of this new heat is generated at or near the surface of the Earth. Below the level of isostatic compensation, the depth at which surficial excesses and defects of density are balanced, there can hardly be much chemical activity and very little friction. An earthquake wave may penetrate to much greater depths, probably to the margin of the nucleus, but its thermal significance diminishes as it recedes from its focus, and below the isostatic level, which is put at about 60 miles, it can not be very great. At greater depths the temperature, whatever it may be, is due to residual heat and is not higher than the average melting point of igneous rocks.

The conditions in the nucleus of the Earth are very different from those in the lithosphere. Here we have a metallic mass more than 6,000 miles in diameter, which is a good conductor of heat. It is practically insulated by a shell of poorly conducting rock at least 800 miles thick. Under such conditions, because of its conductivity, the temperature of the nucleus should be uniform or nearly so throughout and below the melting point of iron, or 1,600° C. This conclusion implies that the nucleus has attained a state of stable equilibrium, which is also indicated by the established fact that the Earth as a whole is rigid. Only near the surface is this rigidity disturbed.

NOTE.—Some valuable determinations of the compressibility of rocks and minerals have recently been published by L. H. Adams and E. D. Williamson (Franklin Inst. Jour., April, 1923). Their data, as applied to the present discussion, show that the granitic rocks are the most compressible, and the denser rocks much less so. Granite is about three times as compressible as iron. From the surface of the earth to its nucleus, therefore, the compressibility diminishes, and the resistance to pressure must steadily increase.

THE DISINTEGRATION OF THE ELEMENTS.

Our direct, experimental knowledge of atomic disintegration began with the discovery by Ramsay and Soddy in 1903 of the emission of helium from radium. This discovery, however, was the outgrowth of two earlier discoveries—that of radioactivity by Becquerel in 1896 and of polonium and radium by the Curies two years later. From these beginnings a new field of chemical and physical research has developed, which is already rich in fundamental discoveries and is represented by a voluminous literature.

The study of radioactivity, however, covers only one phase of the main problem of elemental decay. As soon as it was clearly recognized that the most complex elements were spontaneously decomposing, investigators began to attack the problem along other lines of research, some of them experimental and others mathematical. The atoms that had been regarded as simple were seen to be complex, and it was sought to determine their structure. Attempts were and are still being made to decompose the chemical elements by artificial means, and some significant evidence of disintegration has been furnished by astronomy.

The study of radioactivity is primarily, although not entirely, a study of the radiations which the most complex elements emit. These radiations are of three kinds, known as alpha, beta, and gamma rays, which differ in velocity and in the extent to which they can penetrate an obstacle in their paths, such as a sheet of aluminum foil. The different products of radioactivity—that is, of atomic disintegration—are identified chiefly by the character of their radiations. The alpha rays are composed of helium atoms, the beta rays are "atoms" of negative electricity, and the gamma ray is regarded as possibly an electrically neutral doublet of two electrons of opposite sign. Through the study of these radiations more than thirty new substances have been discovered, which have received names and to which have been given atomic weights (except in the actinium series) and atomic numbers. In the following table, which is abridged from that recently published by the International Commission on the Chemical Elements, the present state of our knowledge of the radioactive elements is well shown. Some details, not needed in the present discussion, have been omitted from the complete table. The letter T at the head of the first column refers to the "period" of each substance—that is, the time in which the quantity of an "element" is diminished to one-half, the "half-life period," as it is commonly called. The column headed "radiation" gives the characteristic rays which the substances emit.

This table evidently has no claim to finality. It is a valuable summary and classification of experimental data, but it also contains implications which sooner or later must be revised. The basic facts are as follows: Uranium and thorium are slowly decaying, and in doing so they generate series of products which are also unstable and which seem to end in the formation of lead. A few of these products are long-lived, with periods measured by years; others change with almost incredible swiftness, and for some of them the periods consist only of minutes, or even of small fractions of a second. The disintegration of uranium and its products follows two distinct lines—one through ionium and radium, the other forming the actinium series. The thorium series, so far as we know, is single.

Each of the three series given in the table divides at about its middle into two parts, with the line of demarcation marked by the appearance of the gaseous emanations of radium, actinium, and thorium X. For these emanations the names "radon" (formerly niton), "actinon," and "thoron" are proposed. These emanations are short-lived and give rise as they decay to what are called "active deposits," which are nonvolatile and can be collected and concentrated upon negatively charged metallic points or surfaces. These deposits in turn decay, and so on to the end of the series.

Now, without doubting the accuracy of the experimental data upon which the foregoing table is based, we may examine the inferences that are drawn from them. Here we must again point out the difference between normal and abnormal or defective elements. The normal elements are those which were developed in the ordinary course of evolution; the abnormal elements are those which were produced by decay. The difference between the two classes is very definite. The normal atoms are believed to be veritable storehouses of potential energy. In the series of radioactive elements that energy is becoming partly kinetic. The distinction is perfectly clear. Some of the products of radioactivity are too ephemeral to be called elements at all. They represent matter in a state of transition from one form to another, and the atomic weights assigned to them are purely hypothetical. As for uranium and thorium, they are partly decayed and are still decaying, but they must have been originally developed as normal elements under conditions of pressure or temperature of which we know nothing. To quote an apt remark of Eddington,[35] in his lecture upon the borderland between astronomy and geology: "In radioactivity we see a mechanism running down which must at some time have been wound up." This fits the cases of uranium

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[35] Eddington, A. S., Nature, Jan. 6, 1923.

The radioactive elements.

The uranium-radium series.

T.	Name.	Symbol.	Atomic weight.	Atomic number.	Isotope.	Radiation.
4.67×10^{9} years	*Uranium I*	UI	238	92	U	α
24.6 days	*Uranium X_1*	UX_1	234	90	Th	β
1.15 minutes	*Uranium X_2*	UX_2	234	91	Pa	β (γ)
2×10^{6} years	*Uranium II*	UII	234	92	U	α
6.9×10^{4} years	*Ionium*	Io	230	90	Th	α
1690 years	*Radium*	Ra	226	88	Ra	α $(\beta+\gamma)$
3.85 days	*Radon*	Rn	222	86	Rn	α
3.0 minutes	*Radium A*	RaA	218	84	Po	α
26.8 minutes	*Radium B*	RaB	214	82	Pb	β (γ)
19.5 minutes	*Radium C*	RaC	214	83	Bi	99.97% β and γ
10^{-6} second	*Radium C′*	RaC′	214	84	Po	α
16.5 years	*Radium D*	RaD	210	82	Pb	(β and γ)
5.0 days	*Radium E*	RaE	210	83	Bi	β
136 days	*Radium F* (Polonium)	RaF (Po)	210	84	Po	α (γ)
....	*Radium Ω′* (Lead)	Ra Ω′ Pb^{206}	206	82	Pb	....
....	*Radium C*	RaC	214	83	Bi	0.03% α
1.4 minutes	*Radium C″*	RaC″	210	81	Tl	β
....	*Radium Ω″*	RaΩ″	210	82	Pb	....

The actinium series.

....	*Uranium ?*	....	?	92	U	α
1.04 days	*Uranium Y*	UY	?	90	Th	β
1.2×10^{4} years	*Protoactinium*	Pa	?	91	Pa	α
20 years	*Actinium*	Ac	?	89	Ac	—
19.5 days	*Radioactinium*	RdAc	?	90	Th	α (β)
11.4 days	*Actinium X*	AcX	?	88	Ra	α
3.9 seconds	*Actinon*	An	?	86	Rn	α
2.01×10^{-3} second	*Actinium A*	AcA	?	84	Po	α
36.1 minutes	*Actinium B*	AcB	?	82	Pb	(β and γ)
2.15 minutes	*Actinium C*	AcC	?	83	Bi	α
4.71 minutes	*Actinium C″*	AcC″	?	81	Tl	β and γ
....	*Actinium Ω″* (hypothetical)	Ac Ω″	?	82	Pb	....

The thorium series.

1.31×10^{10} years	*Thorium*	Th	232	90	Th	α
6.7 years	*Mesothorium 1*	MsTh1	228	88	Ra	—
6.2 hours	*Mesothorium 2*	MsTh2	228	89	Ac	β and γ
2.02 years	*Radiothorium*	RdTh	228	90	Th	α (β)
3.64 days	*Thorium X*	ThX	224	88	Ra	α
54 seconds	*Thoron*	Tn	220	86	Rn	α
0.14 second	*Thorium A*	ThA	216	84	Po	α
10.6 hours	*Thorium B*	ThB	212	82	Pb	β and γ
60 minutes	*Thorium C*	ThC	212	83	Bi	65% β
10^{-11} second	*Thorium C′*	ThC′	212	84	Po	α
....	*Thorium Ω′* (Lead)	Th Ω′ Pb^{208}	208	82	Pb	....
....	*Thorium C*	ThC	212	83	Bi	35% α
3.1 minutes	*Thorium C″*	ThC″	208	81	Tl	β and γ
....	*Thorium Ω″* (Lead)	Th Ω″ Pb^{208}	208	82	Pb	....
....	*Potassium*	K	39.1	19	K	β
....	*Rubidium*	Rb	85.5	37	Rb	β

and thorium exactly. When the conditions that permitted the evolution of uranium ended, then disintegration began.

The atomic weights of normal uranium and thorium are unknown.

The values assigned to them really represent mixtures of the normal elements with some of their decomposition products, of which we know only those that are revealed by their radiations. That there may be residues left behind which are as yet undiscovered seems to be unquestionable. The actual determinations of atomic weight were made with masses of material containing millions of atoms, some of them intact and others represented by unexpelled products of disintegration. If all the atoms were broken down at once, there would be neither uranium nor thorium left. Furthermore, the atomic weight assigned to thorium is affected by another complication. It is doubtful whether any thorium compounds are known which are quite free from its isotope, ionium. The atomic weight of ionium has been shown by Honigschmid to be at least as low as 231.5, and probably lower. That of purified thorium must certainly be higher than the accepted 232.2, but the exact value is undetermined. The presence of ionium gives it too low a value.

The atomic weights and numbers assigned to the products of radioactive decay are, with a few exceptions, hypothetical. The atomic weight of radium as actually determined is 225.95, and it falls into place in the periodic system. For its emanation, radon, the value is near 222, but the determination is not as exact as is desirable. Radium, moreover, and also radon are still decaying, and the values given to them are therefore subject to the same uncertainties as those which affect the atomic weights assigned to uranium and thorium. If corresponding normal elements exist, their atomic weights should be somewhat higher. The so-called isotopes of lead will be considered later.

From what has been said in the preceding paragraphs it is evident that the atomic weights and numbers assigned to the radioactive "elements" are in need of careful revision. The atomic weights start from two that are certainly in error and are developed on the assumption that each step downward is due entirely due to the loss of alpha particles. But does that loss represent all the change which has taken place? And how large a proportion of the atoms in a given mass of uranium or thorium has been decomposed? Furthermore, is Moseley's law of atomic numbers applicable to products of decay—for example, to radium C′? That product of radioactivity has a period of only 10^{-6} second; it comes into existence, pays a flying call on atomic number 84, and then vanishes. To call such a substance an element verges on absurdity. Moseley's law may be valid for the normal elements, but it has not yet been tested throughout the scale of atomic weights. The evidence in its favor is incomplete. In the actinium series no atomic weights are assumed, for the reason that the exact ancestry of actinium is still uncertain. None of these doubts, however, attaches to the atomic weights of potassium and rubidium, two metals which are feebly radioactive but are independent of the uranium and thorium series.

In the table of the radioactive elements six members are reported as isotopes of lead. That is, although the atomic weights assigned to them range from 206 to 214, they are given the same atomic number with lead, No. 82, and appear in the same place in the periodic classification. These isotopes are radium B, radium D, actinium B, thorium B, uranium lead, and thorium lead. Three of them are short-lived and need not be considered further here. Radium D, however, sometimes called "radio-lead," is part of the active deposit of radon; and it has been collected in sufficient quantity for qualitative tests and gives some reactions that are like those of normal or ordinary lead. Its period is 16.5 years, and its hypothetical atomic weight is 210.

The two isotopes that end the radioactive series, uranium lead and thorium lead, are on a different footing from the others. They are obtained from minerals containing them in sufficient quantities for good determinations of atomic weight. These determinations give different values for the lead from different sources, showing that mixtures of normal lead with its isotopes are of common occurrence in radioactive minerals. In the most perfect and brilliant crystals of uraninite, which are found in granitic pegmatites, normal lead seems to be absent, and the isotopic lead has an atomic weight very close to 206, the lowest value yet found. For thorium lead, derived from ores of thorium, the lowest value is 208. Are these the real ends of the radioactive series, or does disintegration proceed still further? So far, this question is not completely answered.

The existence of these isotopes has led to a belief, or rather a suspicion, that ordinary lead is a mixture and not a single definite substance. How far is this suspicion verified? Is the atomic weight of ordinary lead constant or variable? To answer these questions Baxter and Grover made elaborate series of analyses of lead bromide and chloride from very different sources. Lead was obtained from galena, cerusite, vanadinite, and wulfenite, and the minerals came from widely separated localities—namely, Idaho, Arizona, Washington, Missouri, Germany, and Australia. Four different minerals and seven localities furnished the material for the determinations, and commercial lead nitrate was also included in the investigation. Four series of determinations were made, giving average values for the atomic weight of lead ranging from 207.18 to 207.23, an extreme difference of 1 part in 4,144, which is quite within the allowable limits of experimental uncertainty. The atomic weight of normal lead is a definite quantity and not a statistical average of the different values found for its isotopes. To maintain such a uniform average the isotopes should always be mixed in exactly the same proportions, and that is extremely improbable.

One very uncertain assumption has been made as to the nature of isotopes. Those of lead, for instance, are said to be chemically identical and not separable by chemical methods. That simply means that no such separation has yet been effected; but there is no proof that it may not be effected in the future. The prediction of impossibilities is not always verified. Many failures are on record.

That the products of radioactivity are products of decomposition is proved, but their definiteness is not so certain. All or nearly all of them are unstable and undergoing change, some rapidly and others with extreme slowness. Their isotopy, moreover, is largely hypothetical, for how can two products be called isotopic when both are undergoing alteration and at different rates? Only for uranium lead and thorium lead can isotopy be regarded as established, and even for these the claim must be held with reservations. The isotopes differ from normal lead in some physical properties, but that they are its equal as regards stability is still uncertain. The stable product of evolution and the products of decomposition are not quite the same. Their similarity may be illusive. This possibility should not be ignored.

Reference has already been made to Aston's work on "mass spectra"—work which is of great value, regardless of any interpretation that may be put upon it. Are his isotopes substances of the same order as those that appear in radioactivity?

The "mass spectra" described by Aston[36] represent an artificial disintegration of elements, and his process is roughly as follows: An element or one of its compounds is bombarded by powerful positive rays in a magnetic field. The rays, differently deflected, finally impinge upon a carefully calibrated photographic plate, upon which they give lines that are interpreted as belonging to isotopes. From the position of these lines the atomic weights of the isotopes are determined within a supposed accuracy of 1 part in 1,000, or one-tenth of 1 per cent, a rather large uncertainty.

It is not necessary for present purposes to go into the details of Aston's work. They are fully given in his book on isotopes. Suffice it to say that his apparatus, his "mass spectograph," is very complicated, and his technique is exceedingly refined. The essential fact is that the elements undergo certain changes when subjected to the action of positive rays. Other methods for attaining results similar to Aston's have been developed by Sir J. J. Thomson and by A. J. Dempster, but they also are applications of what is called positive-ray analysis. The products of these analyses, regarded as isotopic, are given in the following table, which is abridged from the table published by the International Commission on the Chemical Elements in 1923. The figure relating to glucinum is due to G. P. Thomson; those of magnesium, calcium, and zinc, to Dempster; all the others are Aston's. A number inclosed in parentheses is doubtful.

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[36] Aston, F. W., Isotopes, London, 1922.

Isotopes.

Element.	Atomic number.	Atomic weight.	Minimum number of isotopes.	Masses of isotopes.
H	1	1.008	1	1.008
He	2	4.00	1	4
Li	3	6.94	2	7; 6
Gl	4	9.02	1	9
B	5	10.9	2	11; 10
C	6	12.005	1	12
N	7	14.008	1	14
O	8	16.000	1	16
F	9	19.0	1	19
Ne	10	20.2	2	20; 22
Na	11	23.00	1	23
Mg	12	24.32	3	24; 25; 26
Al	13	27.0	1	27
Si	14	28.1	2	28; 29; (30)
P	15	31.04	1	31
S	16	32.06	1	32
Cl	17	35.46	2	35; 37
A	18	39.9	2.	40; 36
K	19	39.10	2	39; 41
Ca	20	40.07	(2)	40; (44)
Fe	26	55.84	(1)	56; (54)?
Ni	28	58.68	2	58; 60
Zn	30	65.37	4	64; 66; 68; 70
As	33	74.96	1	75
Se	34	79.2	6	80; 78; 76; 82; 77; 74
Br	35	79.92	2	79; 81
Kr	36	82.92	6	84; 86; 82; 83; 80; 78
Rb	37	85.45	2	85; 87
Sn	50	118.7	7 (8)	120; 118; 116; 124 119; 117; 122; (121)
I	53	126.92	1	127
Xe	54	130.2	7 (9)	129; 132; 131; 134; 136; 128; 130; (126); (124)
Cs	55	132.81	1	133
Hg	80	200.6	(6)	(197–200); 202; 204

What do the figures in the last two columns of the foregoing table really mean? Do they represent isotopes in the accepted meaning of the term, which are merely separated by the bombardment? Or are they a record of an elemental disintegration? These alternative interpretations are both tenable, and each one can be sustained by cogent arguments. The second question is answered by Aston in the affirmative; and his views have been generally accepted or at least favored. On the other hand, the isotopes of the radioactive series are definitely products of decomposition, and those of the mass spectra may be of the same order.

The last column of the table is extremely suggestive. The simplest elements, those of low atomic weight, show little or no isotopy. Twelve of them are simple substances and may be called pure or normal elements. Nine of them, up to and including nickel, are doubled, and two are represented as triplets. With zinc a greater degree of complexity appears, which, with some exceptions, tends to increase as the atomic weights become larger. This increase, however, represents only a distinct tendency, not a definite law. How far this rule may hold remains to be determined; and it is extremely desirable that the mass spectra of the elements above mercury in the scale of atomic weights should be examined—namely, those of thallium, lead, bismuth, thorium, and uranium. Such an examination would render a direct comparison with the radioactive series possible. Would the mass spectrum of lead, for example, show the same isotopes as those which have been revealed by radioactivity? That of uranium, also, should be very instructive. The most complex elements are the most easily decomposable and should show the greatest number and variety of fractions.

So far the evidence favors the hypothesis of decomposition; but there is also evidence to support the isotopic theory. By diffusion or by distillation three elements—namely, chlorine, zinc, and mercury—have been separated into fractions that differed in density and in atomic weight. Harkins and his colleagues,[37] by fractional diffusion of gaseous hydrochloric acid, have partially separated it into two portions, one heavier and the other lighter than the ordinary compound. The heavier portion gave an atomic weight for chlorine of 35.4918, which is 0.1 per cent higher than the accepted value, 35.46. The latter value has been determined with the greatest accuracy and is probably correct within 1 part in 10,000. Results similar to those of Harkins and Hayes, but by a different method, have been obtained by Brönsted and Hevesy,[38] who separated hydrochloric acid into two fractions corresponding to a difference of 0.024 in the atomic weight of chlorine. The chlorine atom, then, seems to be a doublet; but the remarkable uniformity of its chemically determined atomic weight is difficult to explain. A mere mixture of two isotopes could hardly be so definite unless all the compounds of chlorine that were used in the determination of its atomic weight had a common origin. That possibility is still under investigation. Is the chlorine of volcanic emanations, of meteoric iron, of oceanic salts, and of igneous rocks always the same thing, and of one definite atomic weight?

By fractional distillation mercury has been separated into two portions, one heavier than

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[37] See especially Harkins, W. D., and Hayes, A., Am. Chem. Soc., Jour., vol. 43, p. 1403, 1921.

[38] Brönsted, J. N., and Hevesy, G., Nature, vol. 107, p. 619, 1921.

the other, as in the case of chlorine. Harkins and Madorsky[39] evaporated mercury in a vacuum and obtained two fractions that gave differences from the accepted atomic weight of the metal of +0.052 and −0.044. Brönsted and Hevesy,[40] by a similar process, obtained results of the same order. The same chemists, however, in a later investigation,[41] determined the density of ordinary mercury from ten widely separated sources and found differences of only 2 to 6 units in 10 millions. These differences in density correspond to differences in atomic weight of 0.0004 to 0.0012.

By very thorough determinations of atomic weight Hönigschmid and Birckenbach[42] have completed the evidence as to the composite nature of mercury. Brönsted and Hevesy supplied them with samples of their heavy and light fractions, with which the determinations were made—for the heavier fraction, Hg = 200.628 to 200.638; for the lighter fraction, Hg = 200.562 to 200.568. These differences are conclusive. For ordinary mercury the same chemists, aided by M. Steinheil,[43] found Hg = 200.61, the accepted value.

Ordinary or normal mercury, if we may call it so, is therefore uniform in character far within the limits of experimental uncertainty. The same is true of lead, as we have already seen; and the work of Baxter and his colaborers have shown it to be true of iron and nickel. The atomic weights of terrestrial iron and nickel are identical with those of the two meteoritic metals. In order to account for this uniformity we must assume in each case that the component isotopes must always have been mixed in constant and definite proportions.

For the possible complexity of zinc there is only the work of Egerton,[44] who in a preliminary note reports finding small differences in the density of the metal after distillation in a high vacuum. Two fractions gave densities of 0.9971 and 1.00076, when that of the initial substance was taken as unity. These results are regarded as promising.

So far a partial separation of chlorine and mercury into distinct fractions has been accomplished, although the differences between the fractions are very small. A complete separation is yet to be effected, so that each fraction can be weighed and examined by itself. If the mass spectra really represent isotopes there should be twelve possible isotopes of mercuric chloride, ranging in molecular weight from 232 to 241, a difference of 9 units in atomic mass. The fractional crystallization of mercuric chloride, then, or else precipitation of the mercury either by electrolysis or with some suitable reagent, might yield definite results. Other lines of attack upon the problem of separation have been suggested, and they are summarized by Aston in his book. Greater detail is not needed here.

Evidence of an entirely different character as to disintegration of elements has recently been obtained by Rutherford.[45] His procedure, briefly, is as follows: A stream of powerful alpha rays, emitted from a very thin film of radium C, is passed through a current of hydrogen. A number of high-speed hydrogen atoms are liberated, which strike upon a screen of zinc sulphide and produce scintillations that can be observed through a microscope and counted. Between the zinc sulphide and the radioactive source thin screens of mica are inserted, which can be varied in thickness, so as to measure the relative penetrating power of the alpha particles and of the hydrogen atoms. The range of the hydrogen atoms is much greater than that of the alpha rays and so gives a datum for their identification. Their appearance, as found by the scintillations on the zinc sulphide, identifies them as hydrogen.

Suppose, now, that some other gas replaces hydrogen. With nitrogen the same long-range particles appear, this giving evidence that the lighter element is a constituent of the nuclei of the heavier atoms and has been separated from them. With oxygen or carbon dioxide no such change is observed, a very significant difference. The molecular weights of these gases are whole multiples of that of helium, from which carbon and oxygen are supposed to have been built up.

By this general method, with modifications in the case of solid substances, Rutherford has tested all the elements up to atomic weight 40, with the exception of helium, neon, and argon. Several other elements, higher in the

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[39] Harkins, W. D., and Madorsky, S. L., Am. Chem. Soc. Jour., vol. 45, p. 591, 1922.

[40] Brönsted, J. N., and Hevesy, G., Nature, vol. 106, p. 145, 1921.

[41] Zeitschr. anorg. allgem. Chemie, vol. 124, p. 22, 1922.

[42] Honigschmid, O., and Birckenbach, L., Deutsch. chem. Gesell. Ber., vol. 56, p. 1219, 1923.

[43] Idem, p. 1212.

[44] Egerton, A. C., Nature, vol. 110, p. 773, 1922.

[45] Rutherford, Sir Ernest, Nature, vol. 109, pp. 584–586, 614–617, 1922.

scale, were also tested, but none above phosphorus gave positive results. Boron, nitrogen, fluorine, sodium, aluminum, and phosphorus yielded long-range particles, from which it is concluded that hydrogen atoms are contained in their atomic nuclei. Elements with atomic weights that are whole multiples of 4 give no hydrogen particles when bombarded with alpha rays. The hydrogen-helium theory of the constitution of the elements thus receives some support. Will it hold good for the more complex elements? That remains to be seen. Not until an element has been completely disintegrated into identifiable hydrogen and helium can the question be definitely answered. So far only a few atoms among millions have given evidence of atomic disintegration, and we can only guess at what remains after the hydrogen particles have been expelled. However, a promising attempt has been made toward the artificial breaking down of atomic nuclei, but it is only a beginning. It would be unfair to expect much more in so young a field of research.

That the evolution of a star is accompanied by an evolution of the chemical elements seems to be established, at least to a high degree of probability. But is the process ever reversed? This question can be answered in the affirmative. Every now and then an insignificant star, visible only through a telescope, suddenly flashes into great brilliancy, sometimes even rivaling Sirius in brightness. This condition lasts for a short time, and then the "new star" gradually fades away and returns to something like its former insignificance. So much is shown by the telescope alone, but when the spectroscope is also used much more is revealed. The spectrum and therefore the composition of the star has changed, and a complex system has reverted to something simpler. When the reversal is complete its end product is a planetary nebula with a Wolf-Rayet star as a nucleus. In some cases the reversal does not go so far, and these exceptions are probably due to differences in the violence of the outburst that was revealed by the sudden appearance of the supposedly new star. The term new, however, is hardly appropriate: what has really happened was the almost instantaneous transformation of a dwarf star into a giant. In recent years the complete reversion to the nebular type has been repeatedly observed and recorded upon photographic plates.[46]

The close relation between planetary nebulae and Wolf-Rayet stars has been emphasized by Adams and Pease and also by Wright. Adams and Pease even go so far as to suggest that some of these peculiar stars were probably at some former time novae from which the nebular gases have disappeared. This is not at all improbable, for the spectra of the Wolf-Rayet stars are found to contain many lines of no known origin. Do they represent decomposition products, the end results of atomic disintegration? The novae at the summit of their careers have enormously high temperatures, at which few of our familiar elements could exist. The conclusion is almost inevitable that the process of elemental evolution has been reversed, but if that is true, what are these decomposition products, and how can they be included in the scale of atomic numbers? To this question no answer can yet be given. The evidence of disintegration, however, seems to be very strong.

To what cause, now, can we attribute the phenomena of the novae? On this subject there are two principal hypotheses. One assumes a collision between two stars, two huge masses, moving with great velocity and so generating the heat that is revealed by the brilliancy of the new star. This hypothesis, however plausible it may be, is not now generally held and needs no further consideration here. The probability of such collisions is very slight.

The other hypothesis, which seems to be more probable, assumes that a single star passes through a dark nebula, or else through a cloud of meteoric dust, with retardation of motion, attendant friction, and therefore a great development of heat. The same thing happens, but on a much smaller scale, when a meteorite enters the atmosphere of the Earth. The difference is merely one of degree. In the larger body the heat is sufficient to disintegrate the elements; in the smaller it only melts a thin film on the surface of the falling mass which is broken up into fragments.

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[46] For examples see Cannon, Annie J., Harvard Coll. Observatory Annals, vol. 81, No. 3, 1920; Adams, W. S., and Pease, F. G., Nat. Acad. Proc., vol. 1, p. 391, 1915, and Astrophys. Jour., vol. 40, p. 294, 1914; Wright, W. H., idem, p. 466. Nova Geminorum No. 2 and Nova Aquilae No. 3 are two of the most typical instances of the reversal of a star to a primitive type. I am indebted to Professor Harlow Shapley for Miss Cannon's paper on Nova Aquilae.